INVESTIGATING THE IMPACT OF HIGH-RISE BUILDING MORPHOLOGY ON ENERGY CONSUMPTION IN HOT CLIMATES

BY

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DEDICATION

I dedicate this research in affection and admiration to all my Family members, Friends and all my Well-wishers in the Kingdom and Abroad.

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First and Foremost I thank ALLAH (SWT) for blessing me with good health and all skills and abilities; that have been my asset in pursuing my Masters. I would also praise the Almighty for blessing me with the opportunity to pursue my education in a university that I always fancied since childhood. I am grateful to my Grandparents who have given me prayers in abundance without which I wouldn't have been in a position I am in today.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

$\mathbf{I}_{dn}$	:	Direct Normal Component
$\mathbf{I}_{d}$	:	Diffused Component
$\mathbf{I}_{r}$	:	Reflected Component
$\mathbf{I}_{ann}$	:	Annual Incident Radiation falling on a surface
$\mathbf{I}_{ann,max}$	:	Annual Incident Radiation falling on a surface that receives maximum Radiation.
SOF	:	Solar Orientation Factor
RC	:	Relative Compactness
SHGC	:	Solar heat gain coefficient
VT	:	Visual transmittance
LOD	:	Level of detail
ASHRAE	:	American Society of Heating, Refrigerating and Air-Conditioning Engineers.
IESNA	:	Illuminating Engineering Society of North Americas
LPD	:	Lighting Power Density
AEC	:	Annual Energy consumption
PI	:	Parametric indicator

ABSTRACT

Full Name : Ejaaz Ahmed

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Energy consumption is fast increasing with globally rising demand in developing countries. Saudi Arabia being no exception where buildings have found to consume a significant 70 to 79% of the total energy produced. This is as a result of the enormous demand placed on the buildings' cooling systems as a result of harsh climatic conditions. Since the building envelope segregates the internal building and external environments, its characteristics and morphology play a vital role in determining heat exchange and subsequent energy savings. In the quest of adapting an "International Style" of architectural design, high-rise contemporary building forms are emerging that are characterized by fully glazed facades and complex geometries that make the interaction with the harsh surroundings challenging to analyze. Moreover the limitation of energy simulation software in modeling such contemporary building forms contributes to less understanding of their forms impact on building energy performance. This study therefore investigates the impact of contemporary high-rise building forms (**morphology**) in hot climates represented by the climate of Riyadh. The objectives are to quantify the magnitude of impact corresponding to architectural and form-based design decision and to develop energy-efficiency guidelines that will assist architects and designers to synchronize their architectural ambitions with sustainability principles. The objectives were achieved by overcoming the limitation of the energy modeling and simulation software (*DesignBuilder)* by linking it to a 3D modeling software (*SketchUp*) via *Gmodeller*. Seven theoretical models and five case study models were simulated and compared to static cubical base case in order to identify form-based parameters that influence heat exchange and energy efficiency. It was found that *Incident Solar radiation* on vertical facades was the most significant parameter that correlated well with cooling energy consumption. The best studied case was found to reduce energy consumption by around 6.0% while the worst case increased energy consumption by around 1%

ملخص الرسالة

الاسم الكامل: **إعجاز احمد**

عنوان الرسالة: **البحث في اثر تغيير تكوين المباني الشاهقة على استهلاك الطاقة في المناخ الحار**

التخصص: **الهندسة المعمارية**

تاريخ الدرجة العلمية: ٢٠١٧

يتزايد استهلاك الطاقة بسرعة مع تزايد الطلب العالمي في البلدان النامية. والمملكة العربية السعودية ليست استثناء حيث وجد أن المباني تستهلك ما بين ٧٠ إلى ٧٩٪ من إجمالي الطاقة المستخدمة. ويعود ذلك إلى الطلب الهائل على أنظمة تبريد المباني نتيجة الظروف المناخية القاسية. وبما أن غلاف المبنى يفصل بين البيئة الداخلية و الخارجية، فإن خصائصه وتشكله يلعب دورا حيويا في تحديد التبادل الحراري وما يترتب عليه من توفير في الطاقة. في السعي إلى استخدام "النمط الدولي" من التصميم المعماري، ظهرالعديد من أشكال المباني المعاصرة الشاهقة و التي تتميز بواجهات كاملة من الزجاج وهندسة التكوين المعقدة التي تجعل التفاعل مع المناطق المحيطة القاسية تحديا للتحليل. وعلاوة على ذلك فإن قصور برامج محاكاة الطاقة في نمذجة أشكال وتكوين المباني المعاصرة يساهم في فهم أقل لتأثير أشكالها على أداء الطاقة. وبالتالي فإن هذه الدراسة تبحث في تأثير أشكال وتكوين المباني المعاصرة (**التشكل**) في المناخات الحارة التي يمثلها مناخ الرياض. وتتمثل الأهداف في تحديد حجم الأثر على توفير للطاقة و الذي يتناسب مع قرار التصميم المعماري القائم على **التشكل** ، كما تهدف الى وضع مبادئ توجيهية بشأن كفاءة استخدام الطاقة تساعد المهندسين و المعماريين والمصممين على توافق طموحاتهم في التصميم المعماري مع مبادئ الاستدامة. وقد تحققت الأهداف من خلال التغلب على قصور طرق ومراحل نمذجة المباني **المتشكلة** باستخدام برامج نمذجة و محاكاة الطاقة (DesigBuilder) من خلال ربطه مع برنامج النمذجة ثلاثية الأبعاد (*SketchUp*) و تكاملهما مع برنامج (*Gmodeller*). وقد تم محاكاة سبعة نماذج نظرية وخمسة نماذج واقعية ومقارنتها مع أداء الطاقة لمبنى مرجعي مكعب التكوين- التشكل من أجل تحديد المؤشرات المرتبطة بشكل و تكوين النماذج و التي تؤثر على التبادل الحراري وكفاءة الطاقة. وقد تبين أن الإشعاع الشمسي الواقع على الواجهات كان أهم المؤشرات التي ترتبط جيدا مع تكوين المبنى و استهلاك طاقة التبريد. وقد وجد أن أفضل تشكل- مبنى حقق تقليل في استهلاك الطاقة بنحو ٦.٠٪ في حين أن أسوأ الحالات زادت استهلاك الطاقة بنحو ١٪.

CHAPTER 1

INTRODUCTION

1.1 Background

Increasing global energy crisis motivates researchers and designers for innovative solutions to conserve energy. Energy consumption is increasing globally with rising demand of developing countries. The supply of energy becomes increasingly difficult with time due to the risk of change in climate associated with usage of fossil fuels in production [1]. On a global level, buildings are major producers of greenhouse gases (30%) and major consumers of energy which comprise 40% of the total produced [2]. In case of a hot climatic region like KSA, buildings consume upto 79.5% of the total electricity produced. Furthermore, 70% of the electricity consumed by a building is by its cooling system to combat the harsh climate [3]. **Fig.1.1** graphically illustrates the energy consumption breakdown by various sectors in KSA.

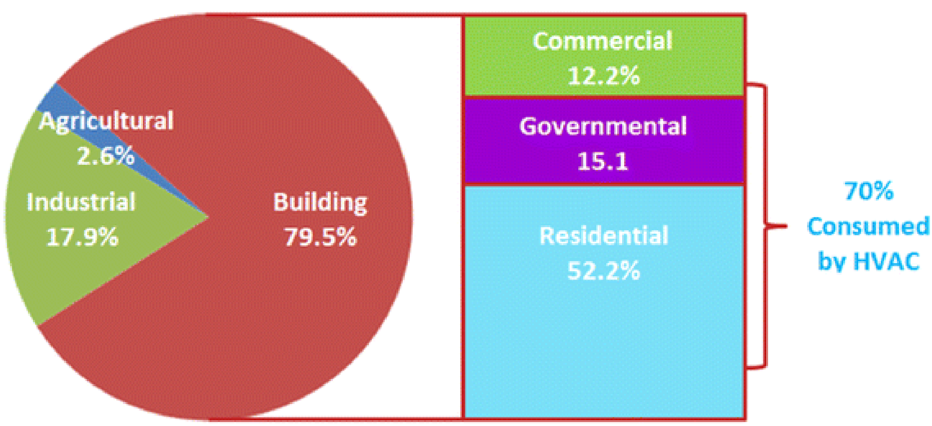


Figure 1.1 Energy distribution in KSA by sector [3]

Since the building envelope segregates the external environment from the internal, it plays a determinant role in heat exchange and energy savings. The characteristics and morphology of the envelope alters the amount of solar energy incident and transmitted into the space [4]. Josifas Parasonis (2012) found out that buildings with identical areas but distinct envelope forms portray discrete energy demand at the operation level.

Most of the studies on building form and energy focus on static shapes, while the current era has witnessed a paradigm shift in buildings architectural design due to the advancement of design tools, material technology and construction methods, leading to the design and development of non-static non orthogonal building forms [5].

Vollers [6] developed a scheme to classify such buildings based on their overall geometry. He analyzed the forms of existing contemporary skyscrapers and categorized them as extruders, twisters, rotors, tordos, free shapers and transformers. The graphical representation of the classification is depicted in **fig 1.2**.

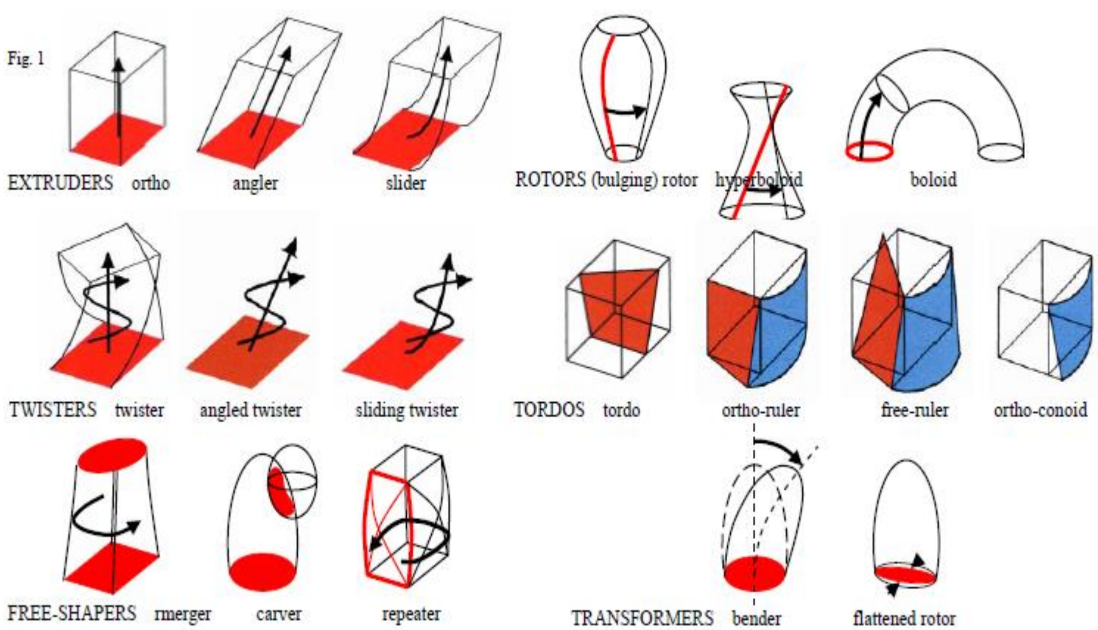


Figure 1.2 Building morphology categorization [6]

Alaghmandan et.al (2014) surveyed world tallest 73 skyscrapers and analyzed them for various parameters including building form. They categorized buildings forms as– Simple, Curvilinear, Setback, Tapering, Adding Opening and Twisting.

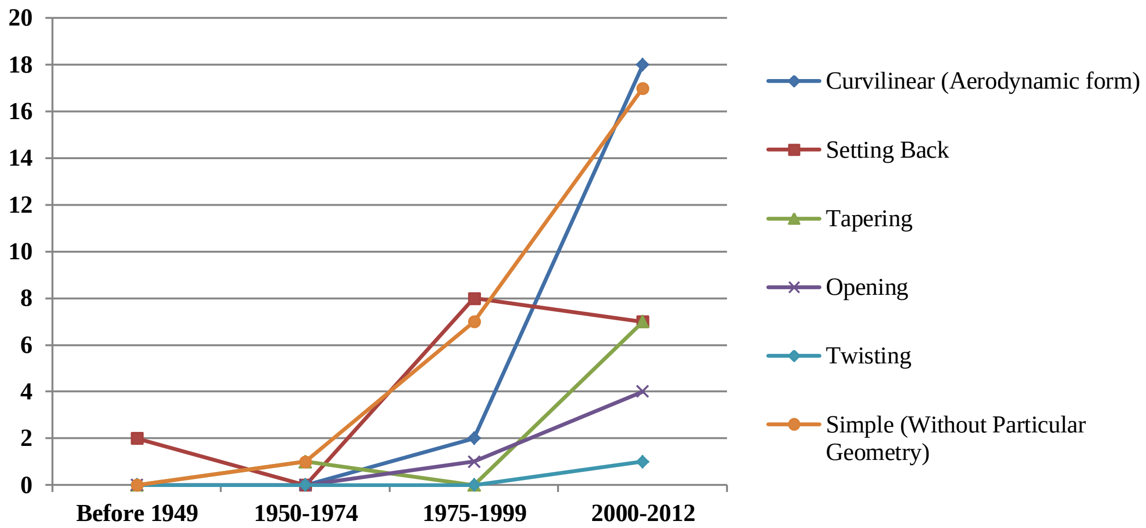


Figure 1.3 Skyscraper forms over the timeline [7]

Based on the graphical illustration in **Fig 1.3**, the analysis shows that curvilinear forms have shown the highest growth rate over the timeline and have the steepest slope followed by tapering and twisted forms. Simple forms have a rather linear increase rate while a downfall in setback building forms was observed.

The study also signifies that amongst the current world's tallest 73 skyscrapers, 33% of the building forms have no macro modification while the remaining 67% have undergone modifications such as curvilinear, setback, twisting etc.

In quest of identifying the influence of contemporary forms over the energy consumption, the following research questions can be raised:

- Can buildings be designed to meet creativity of architects to achieve aesthetic quality and conserve energy at the same time?
- What are the envelope design parameters that impact energy consumption of buildings the most?

1.2 Problem Statement

The building sector plays a crucial role in environmental degradation. In Saudi Arabian context, increase in population and economic decisions drives the rapid growth of buildings, especially in the high rise sector [8]. These high rises consume much higher energy per resident as compared to a resident of a single dwelling [9]. This is not only a result of their function and operation, but also due to the architectural designs of these high rise buildings which have become diverse in terms of geometric variation, compactness and the type of façade treatment which in turn determines the magnitude of interaction with the surroundings.

As illustrated in **Fig 1.4**, the hot climatic region of Saudi Arabia in particular experiences high temperatures during the peak summer season leading to enormous demand on the cooling load supported by the air conditioning systems which contribute to 70% of the total energy consumption. Passive design strategies employed in the initial design stage can contribute to significant reduction in the consumption of energy throughout the building's life cycle [10].

This study thereby identifies building form as a factor that may alter the amount of heat exchange and if optimized accurately in the initial design stages, it will shell out significant energy savings.

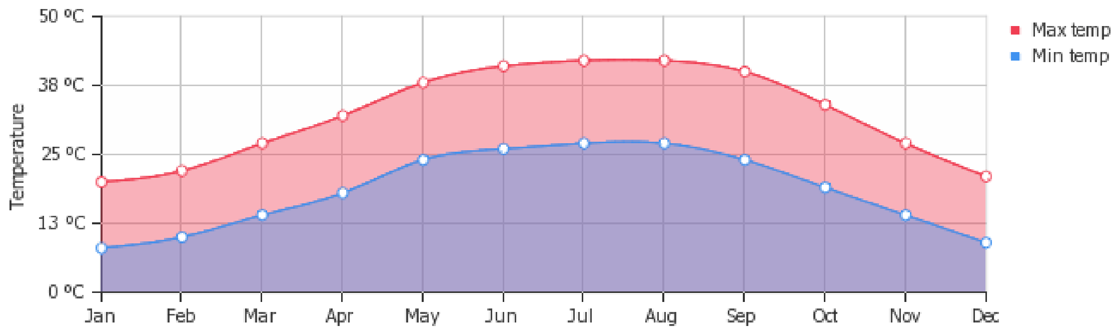


Figure 1.4 Average min and max temperatures in Riyadh, KSA [11]

1.3 Objectives of the study

The main objectives of this research work are to:

- Investigate the impact of building morphology parameters on solar heat gain and energy performance in hot climate
- To develop energy-efficiency guidelines for the early design stage of contemporary morphed building forms in hot climate.

1.4 Significance of the Research

The proposed study will serve as a guide that will assist architects and designers in the early design stage to synchronize architectural ambitions with sustainability principles from the energy perspective.

1.5 Scope and Limitations

- The study will be confined to assessing the impact of building form of office buildings on heat gain in hot climatic condition.
- The number of forms to be examined will be restricted to a suitable number.

1.6 Methodology

An important element of the methodology is modeling contemporary building forms in sophisticated energy simulation software.

In order to accomplish the aforementioned objectives, a research methodology is proposed as follows:

1.6.1 Phase I- Literature Review

- A thorough review of literature on similar concepts of building form and heat exchange.
- Studying different parameters related to building form and their respective influence on heat exchange.

1.6.2 Phase II – Modeling and Simulation

To conduct Phase II analysis, a combination of software is required. Modeling geometries will be done in Trimble SketchUp and exported via Gmodeller to Design Builder which is based on Energy plus as the engine for energy simulation.

Phase II will be carried out in two different steps.

Step 1: Theoretical models

- Modeling a base case of a static form complying with ASHRAE 90.1 and simulating its energy performance.
- Analyzing the impact of Window to Wall ratio by comparing energy performance of base case with the current trends of fully glazed buildings.
- Analyzing the impact of Building Form through generation of "Simple generic forms" by morphing the base case with 100% WWR using "morphological actions".
- Simulating the resultant forms and comparing them to the static base case to assess energy performance.

Step 2: Case study models

- Modeling a base case of a static form complying with ASHRAE 90.1 and simulating its energy performance which serves as a reference to case study models.

- Selection of the contemporary case study forms to be modeled and compared based on literature.
- Modeling of selected forms and altering them to reach the same usable area and properties as base case and simulating their energy efficiency.

1.6.3 Phase III – Analysis

- Analyzing solar heat gains through envelope and compare between forms.
- Conducting correlation analysis to develop a relation between studied parameters and the Annual cooling energy consumption.
- Optimizing envelope characteristics to offset energy consumption of any form that displays negative thermal response.

1.6.4 Phase IV –Conclusion and Recommendation

- Suggest energy- efficient guidelines that can be utilized in the early design stage of high rise buildings when building form is of concern.

1.7 Expected outcome

- Quantification of the impact of building morphological parameters on energy consumption.
- Guidelines that will assist Architects and Engineers in making energy efficient Form based- decisions in the initial design stages.

Fig 1.5 illustrates the schematic summary of the research methodology.

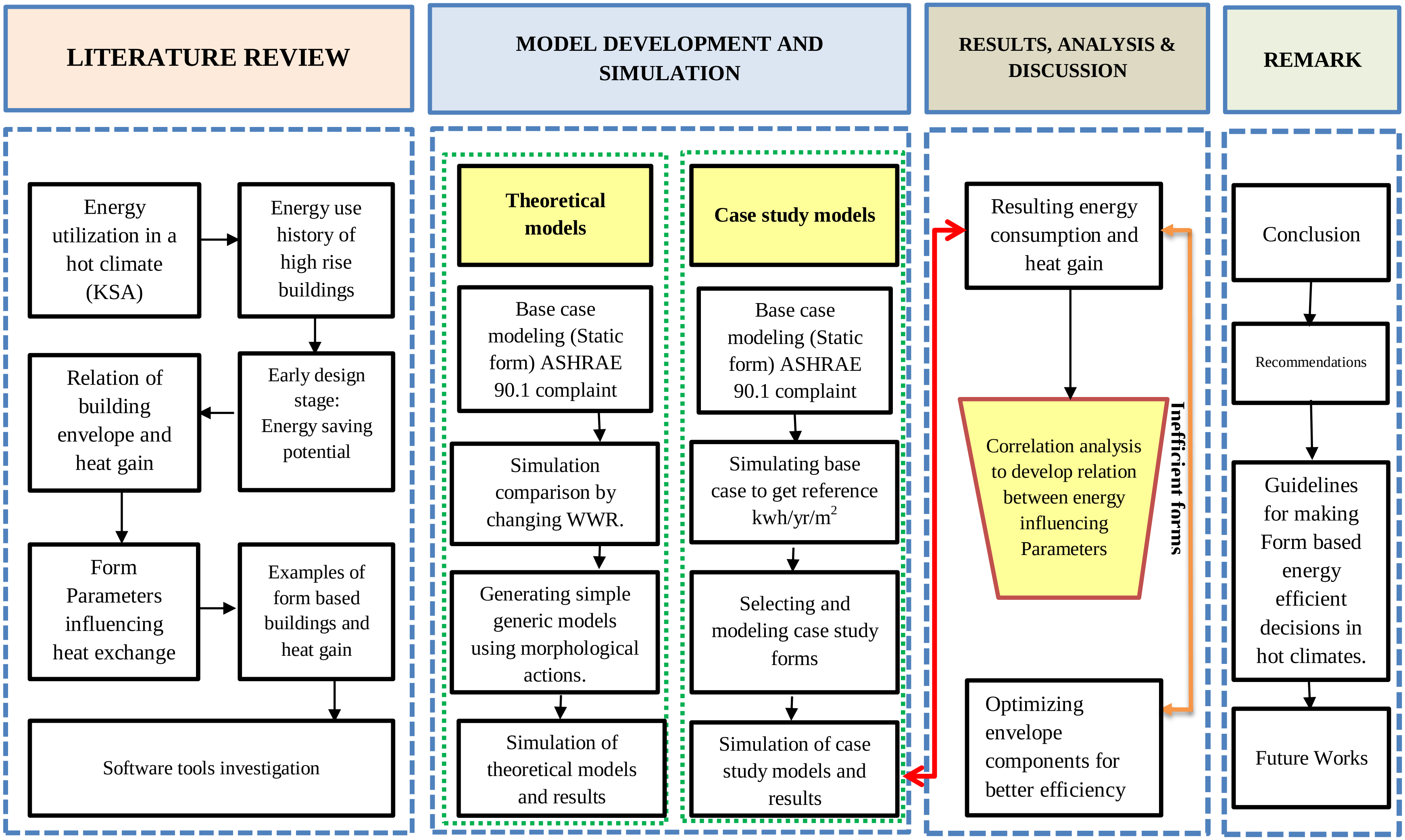


Figure 1.5 Schematic summary of the research methodology

CHAPTER 2

LITERATURE REVIEW

2.1 Energy utilization in a hot climate (Saudi Arabia)

Energy consumption in Saudi Arabia has shown a significant growth in the past 25 years driven by population growth with an average 1.54% annually, increased comfort level demands and excess time spent in the buildings interiors [12]. These factors are indicators to the escalation of energy demand in days to come as illustrated in **Fig 2.1**. Saudi Arabia's consumption per capita is nearly three times the world average [2]. The ministry of water and electricity has reported that the consumption is expected to double by 2030 [13**]**. The kingdom chiefly relies on burning of fossil fuels for generation of electricity which has adverse impacts on the environment. The current and projected rate of consumption may not only detoriate the environmental quality further, but also put the kingdoms reliance on oil export revenue in jeopardy. Since air conditioning is identified as a major contributor to energy consumption, a study suggests that by using energy efficient designs in upcoming construction, the savings in investment will be equivalent to the cost of building 500 MW power plant [14].

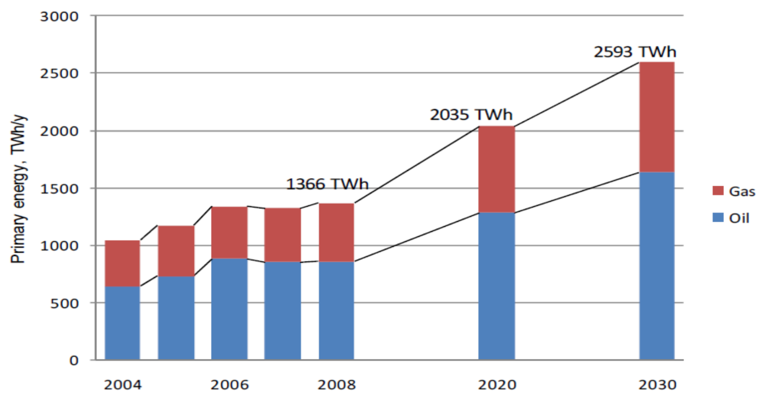


Figure 2.1 Consumption of primary energy in KSA [13]

2.2 Energy use history of high rise buildings

High rise buildings have gone through a series of development over the years driven by innovation in technology and energy demand. Philip et.all (2009) analyzed these changes and categorized over the timeline as 5 different eras.

2.2.1 The first era (1885-1916)

This period had witnessed the first high rise buildings due the invention of vertical transportation ; which were the primary consumers of energy since other technological inventions such as fluorescent lighting and air conditioning were not instigated.

The envelope was characterized by thick load bearing walls which reduced heat exchange with surrounding thereby constituting a thermal barrier. Windows constituted 20-30% of envelope area. Large floor plates and low window to wall ratio resulted in poor indoor lighting levels.

Forms were ‘box shapes’, ‘E’, ‘H’, and ‘U’ etc. to admit light into deeper spaces [15][16].

2.2.2 The second era (1916-1951)

This period witnessed a reduced in the bulky building form due to the blockage of lighting to the streets around. Forms became more slender and shallow floor plates benefited more daylighting thereby reducing artificial lighting load. Air conditioning started becoming common adding to building mechanical load. The envelope still benefited thermally from the bulky mass; using stones, bricks and thick plaster in their façade.

The slenderness of building form was achieved by ‘setback’ design where the building would decrease in bulk in the form of ‘steps’ [16].

2.2.3 The third era (1951-1973)

This period witnessed an increase in glazing ratio by 50-75% as a result of the curtain walls invention. These were single glazed and usually of dark color which contributed to very high cooling loads and higher lighting requirements due to dark colored glazing. Energy consumption doubled as compared to the second generation.

Forms started to resemble the first generation morphology but wrapped around in glass [15].

2.2.4 The fourth era (1973-early 2000's)

Glass facades became popular which lead to the escalation in the glass high rise building count. The era of 1973-1979 witnessed an energy crisis due to excessive energy demand of high rises. This led to development of building standards in the form of building energy codes and also the development of double glazed facades. Clearer glass helped penetrate better daylighting and cavities in the glazing were filled with argon. Collectively these developments led to lower U values of the façade as compared to the third generation buildings.

Though this generation witnessed better façade performance, and increase in internal gains was caused to the increased usage of electronic equipment's such as computers.

Forms still remained majorly similar except for the addition of articulation at the crown level [16].

2.2.5 The fifth era (21st century)

Buildings of this generation have experienced a great leap in overall building form and design with forms having high surface area to volume ratio. Invention and development of modern building materials driven by technological advancements has pushed design boundaries to great extents. Sensitivity to climatic changes have motivated these forms to incorporate energy efficient features which include double skin facades, mixed mode ventilations ,onsite energy production, daylight utilization etc [17][18].

Fig 2.2 compares how building forms of different eras and their construction style impacted the penetration of natural lighting.

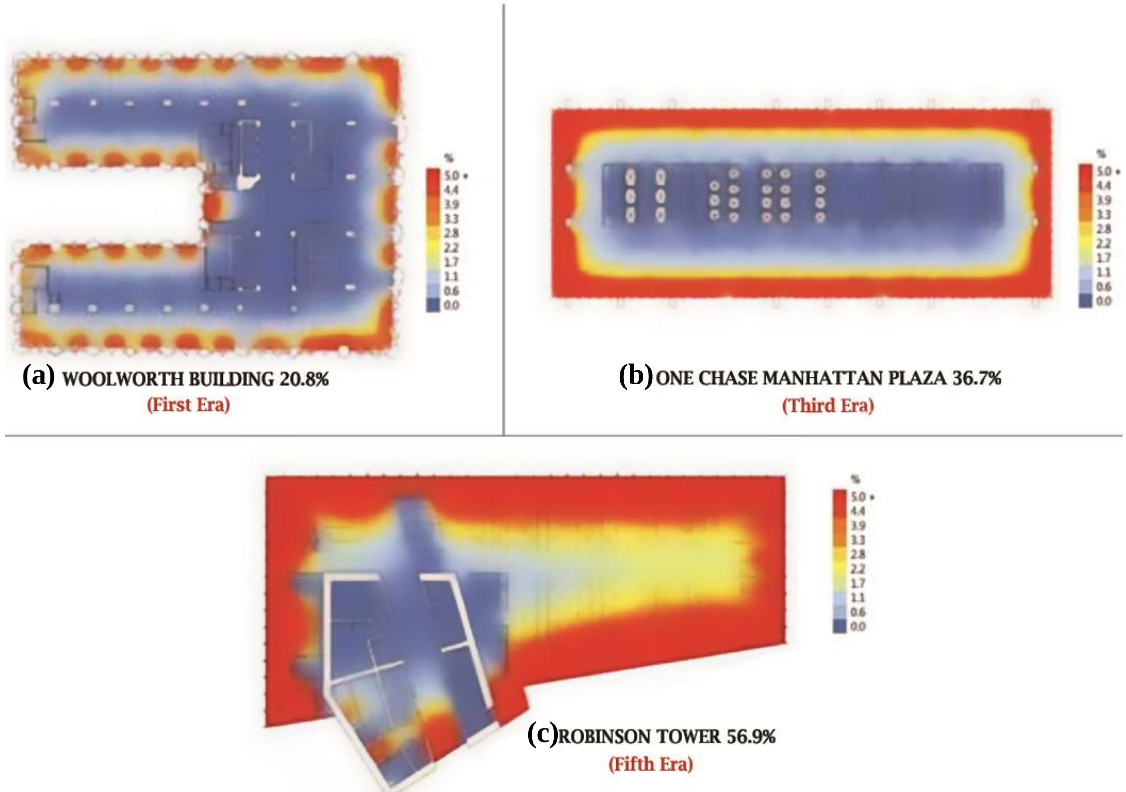


Figure 2.2 Daylight penetration First era (a) vs third era (b) vs fifth era (c) [19]

Building forms also started responding to natural winds to be more aerodynamic, which created but not restricted to ‘tapered’ buildings.

Development of sophisticated modeling tools also provided designers the canvas to experiment with creative geometry and forms. Forms like ‘curvilinear’, ‘twisted’, ‘mixed geometry’ ‘free shapers’ ‘tordos’ ‘rotors’ etc. started becoming evident.

A prime representation of the above is seen in the Capital market authority tower in Riyadh, KSA (**Fig 2.3**). The building uses an inward – outward tapering to create a crystalline form, which is wrapped around in triple glazed insulated glass units with aerogel as filler to increase thermal insulation. This glass is further surrounded by a shroud containing 3mm perforated metal panels that respond to solar radiation and act as shading devices and filter glare to provide comfortable visual environment (**Fig 2.4**) [20].

Figure 2.3 Built form of the CMA tower – Riyadh [20]

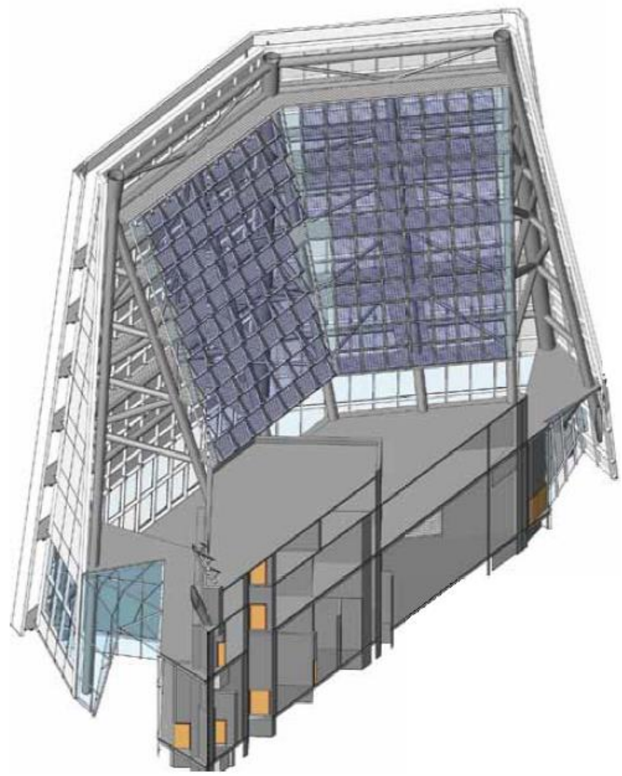


Figure 2.4 Cross section of the CMA towers façade[20]

Another advancement seen in the high rises of this generation was the utilization of their form for onsite energy production by utilizing wind velocity in the upper floors in the form of wind turbines. The Pearl River tower in China is one of the most prominent examples of this type of building form (**Fig 2.5**).

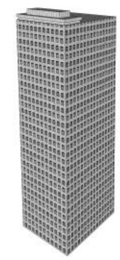
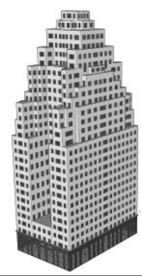
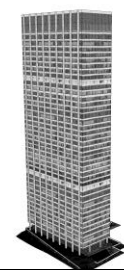
With the façade shaped to force wind through four large openings, vertical axis wind turbines are present that produce approximately 65kW of power each (**Fig 2.6**). Other features such as triple glazing, use of photovoltaic, radiant ceiling, below floor ventilation etc., the building is able to reduce 58% of its dependence on external energy supply [21].

Figure 2.6 Built form of the Pearl tower –China [21]

Figure 2.5 Blow up of the air cavity for enforced air velocity [21]

Table 2.1 summarizes the role played by energy in transforming building forms per generation.

Table 2-1 Summary of building forms and energy factors per generation

Era	**Energy factor in play**	**Form examples**
First (1885-1916)	Thick thermal mass.	  
Second (1916-1951)	Slenderness to reduce lighting loads.	  
Third (1951-1973)	High glazing ratio to further reduce lighting loads	  
Fourth (1973-early 2000's)	High performance glazing	  
Fifth (21st century)	Triple glazing, Dynamic shading, on-site energy production	  

2.3 Early design stage- energy saving potential

According to S.walter (2006), Sustainable design principles are less effective if they are force fitted into existing systems, and suggests that the right approach should be in the opposite direction, by considering all these aspects at the early design stage and incorporate it with function [22]. **Fig 2.7** illustrates the functional and financial benefits of considering energy saving strategies at the early design stage.

Integration of passive energy-efficient architectural solutions at the early design stage ensures lower energy consumption during its operation stage over its lifecycle and reduces the negative impact on the environment [23]. The energy efficient strategies are not restricted to altering thermal properties of materials, but also include the shape, orientation, the placement of transparent envelope elements, the facades color etc [24]. Changes in the buildings shape have a great impact on changes in energy losses, although physical characteristics of the building may remain the same [25].

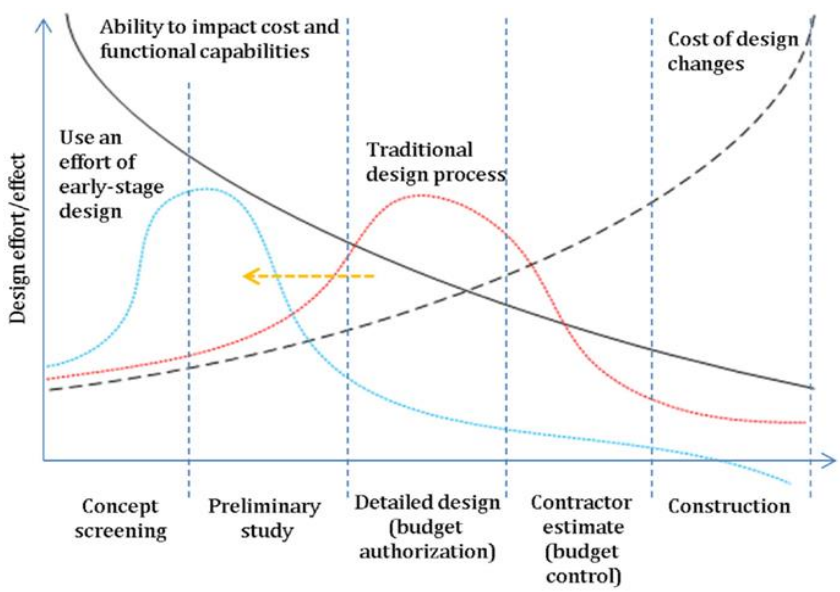


Figure 2.7 Effectiveness of energy efficiency measures at different stages of buildings life [26]

2.4 Relation of building envelope and heat gain

Since the buildings envelope segregates internal and external environments, it plays a vital role in heat exchange. It constitutes of opaque surfaces such as walls, roofs, shading etc. and transparent surfaces such as windows and glazing [27]. Based on the level of heat exchange, the heating/cooling load is determined which constitutes the bulk of electricity consumption. The intensity of heat transfer is largely dependent on the window to wall ratio. **Fig 2.8** provides an example of different window to wall ratios.

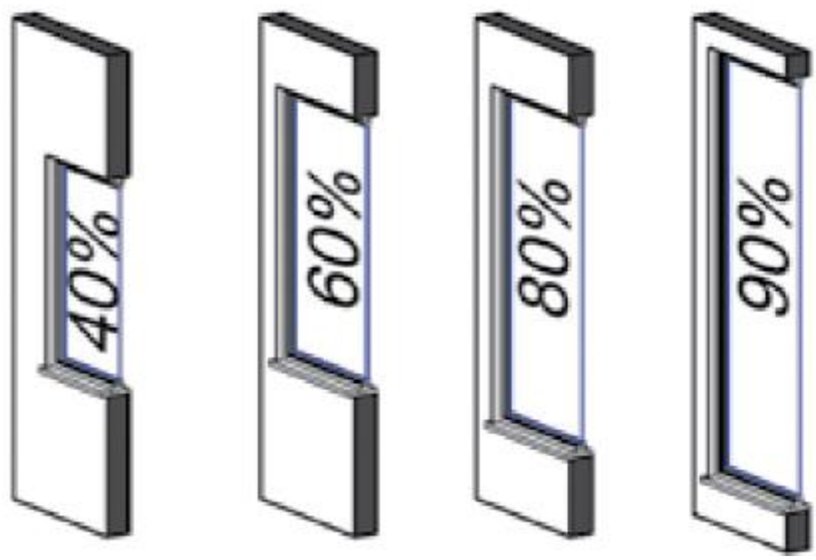


Figure 2.8 Window to wall ratio in % [28]

. An envelope receives solar gain through:

- Conductive heat transfer through opaque surfaces and fenestration
- Direct solar gain through fenestration
- Convective heat transfer through both opaque surfaces and fenestration.

- Thermal absorptivity of building materials

2.4.1 Opaque envelope components

Though high rise buildings are majorly encased with curtain walls, Shuttleworth, ken argue that the level of opacity in such buildings be increased to reduce heat gain [29]. Thereby it is still essential to examine the characteristics and thermal behavior of opaque building envelope components such as walls and roofs.

The rate of conductive and radiative heat transfer (U value) across the assembly relies on its material composition. This is governed by the thermal resistance properties of each material used in the composition (R-value). Higher the R value, higher is the materials resistance to heat.

In a hot climate like Saudi Arabia, Layers of insulation are introduced in wall and roof assemblies to minimize the rate of heat transfer.

A study conducted in Riyadh to establish the ideal position of insulation in the wall assembly. The Study compared single insulation (7.8cm) on the inside , double insulation (3.9+3.9cm) placed in middle and outside and triple insulations(2.6+2.6+2.6cm) placed on outside, inside and middle layers of the wall, with the thickness of insulation being divided the number of insulations increased. It was found that the assembly with triple insulation placed in different regions of the wall assembly served to be more effective as compared to single insulation by reducing peak cooling load by 20% [30].

2.4.2 Transparent envelope components

Heat transfer through a transparent component is dependent on its U value and the solar heat gain factor which is defined as the fraction of solar heat that gets transmitted through a glass surface. SHGC varies on factors including glass type, surface treatment etc., and has a value range between 0 and 1. Lower the SHGC value; lower the solar heat that transmits through [31].

Studies show that the amount of solar heat transferred through glazing can be altered by using glass panes of different color, using double/triple glazing, and by adding surface film to reflect heat.

2.5 Form Parameters influencing heat exchange

Various studies have been conducted in the past based on orthogonal building forms, to determine their heat exchange with the surroundings. These studies have been summarized as follows:

2.5.1 Incident radiation

The incident solar radiation falling on a surface can be defined by

$$I_t = I_{dn}\cos\theta + I_d + I_r \tag{2.1}$$

Where:

I_{dn} : Direct normal component

I_{d} : Diffused component

I_{r}: Reflected component

θ: Angle of incidence

The angle of incidence is the angle between the perpendicular of a surface and the solar ray (**Fig 2.9**). As per equation 2.1, lowering the angle of incidence will reduce the direct component which is the major component in determining total radiation; thereby affecting the total radiation.

The solar angle of incidence for a vertical surface can be defined by –

$$\cos\theta = \cos\beta\cos\gamma \tag{2.2}$$

The solar angle of incidence for a horizontal surface can be defined by-

$$\cos\theta = \sin\beta \tag{2.3}$$

where:

β – Solar altitiude,

γ – Surface solar azimuth

The solar angle of incidence for a tilted surface can be defined by –

$$\cos\theta = \cos\beta \cos\gamma \sin£ + \sin\beta\cos£ \tag{2.4}$$

Where

₤ = angle of tilt from the horizontal.

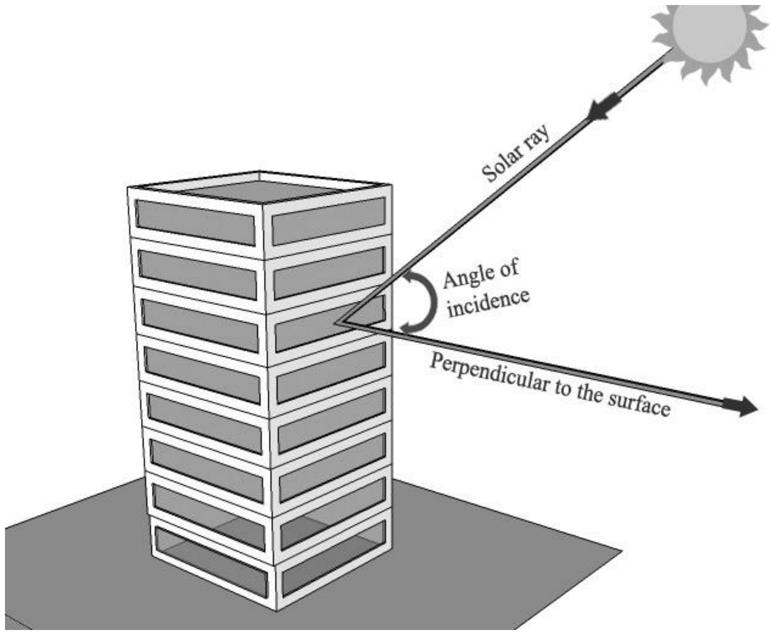


Figure 2.9 Solar Angle of Incidence w.r.t a building face

When a building form is tapered, it impacts the angle of tilt and eventually the angle of incidence. A building tapered inwards decreases the angle of incidence and thereby increase the amount of solar radiation penetrating through. Whereas if a building is inclined outward, it makes the façade “self- shaded” by increasing the angle of incidence thereby decreasing the solar radiation penetrating through and thereby reducing its cooling demand [32].

Zerefos et.al (2012) conducted a study on the variation in incident radiation and its impact on energy consumption. They compared a prismatic building form to a static orthogonal form in terms of solar heat gain as a result of form transformation.

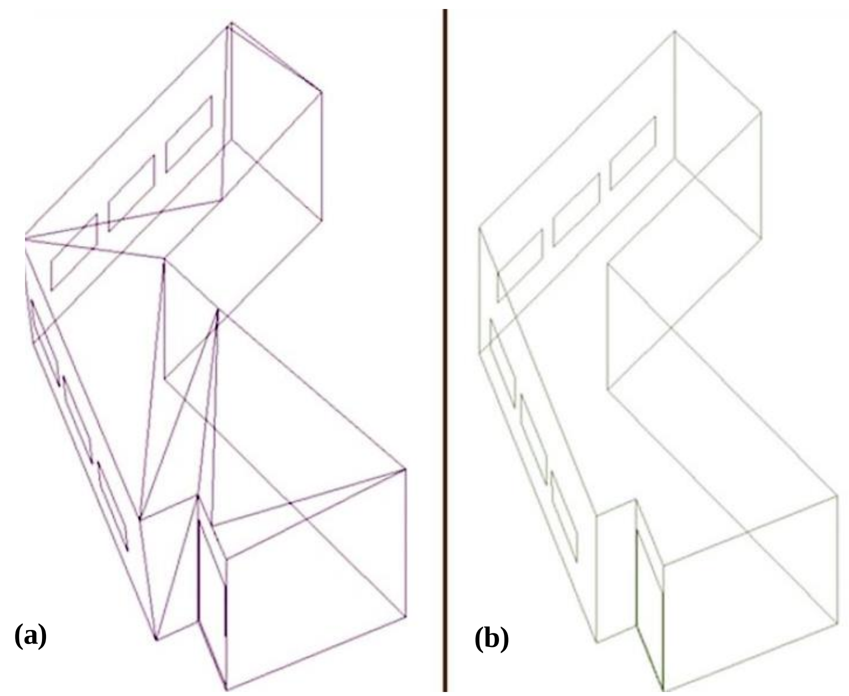


Figure 2.10 Studied forms - Prismatic (a) static (b) [33]

Fig 2.10 demonstrates both the figures where the prismatic building was created by subdividing individual surfaces into triangles and creating positive and negative slopes.

It was noted that the prismatic form was able to reduce solar heat gain in all orientations in comparison to its orthogonal counterpart and resulted in a reduction in annual energy consumption by 7.88% as a result of decreased cooling loads.

Similarly the Surface solar azimuth which is a determinant in calculating the angle of incidence also plays a significant role in determining heat gain.

Surface Azimuth (ψ) can be defined as the angle between the perpendicular to the surface and the South which is determined by the orientation of the surface.

Surface Solar Azimuth (γ) can be defined as the angle between the perpendicular to the surface and the horizontal projection of the sun's ray and can is given by:

$$\gamma = \psi \pm \varphi \tag{2.5}$$

where:

ψ –Surface azimuth,

φ – Solar azimuth

The solar surface azimuth is different for each face of the building, and varies with the change in buildings orientation (**Fig 2.11**).

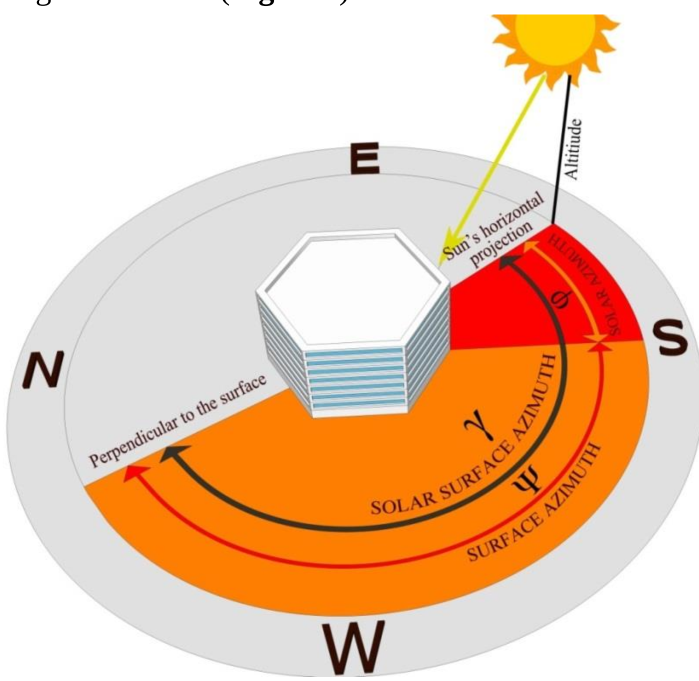


Figure 2.11 Solar azimuth and Surface solar azimuth for a NW facing side

Saleh [34] conducted a study to observe the impact of solar surface azimuth on heat gain through fenestration. This was done by the rotation of windowpanes in a horizontal direction so as to achieve an azimuth angle different from the surface azimuth of the contained wall (**Fig 2.12**). Experiments were carried out for the four cardinal orientations and for summer and winters. It was found that the glass rotation can affect heat gain both positively or negatively depending on orientation and angle of rotation.

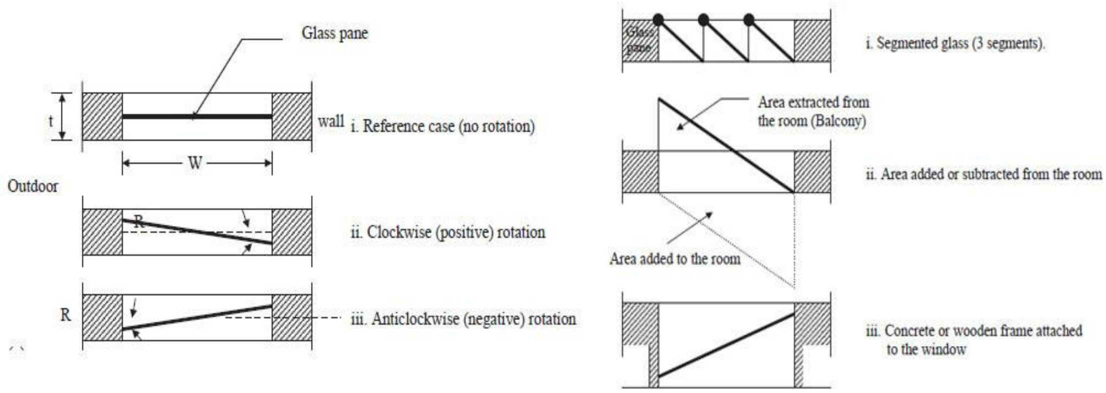


Figure 2.12 Glass azimuth rotations observed [34]

The same concept maybe extended on a building with a twisted form, where different faces of floors have different surface azimuth angles. These varying angles will eventually impact the amount of heat being transferred through the building envelope.

Craig [35] evaluated the optimum orientation to reduce heat by defining the surface orientation factor. The factor is defined by:

$$SOF = I_{ann}/I_{ann,max} \tag{2.6}$$

Where I_{ann} is incident annual radiation on a surface in a particular direction and Iann,max is the incident annual radiation on a surface that receives maximum radiation. Lower the factor, lower is the radiation penetrating through it.

2.5.2 Compactness

Compactness of a building is defined as the ratio of its exterior surface area to the volume contained within. Compactness can be mathematically expressed as:

$$C = A/V \; m^2/m^3 \tag{2.7}$$

Higher value of C indicates higher degree of heat exchange, while lower value indicates lesser exchange of heat; thereby a compact building form will allow lesser heat to be transmitted.

The concept of compactness has been extended by Ourghi et.al [36] to predict the influence of and office buildings shape on the annual cooling load. The compactness was modified to express relative compactness (RC) which is the compactness ratio of the proposed building form to a reference building form with minimum compactness but having the same volume. The relative compactness can be mathematically expressed by:

$$RC = A/V \text{ (Proposed form)} / A/V \text{ (Reference form)} \tag{2.8}$$

Anzi et.al (2009) Conducted experiments to derive the relationship between relative compactness and energy consumption for office buildings in Kuwait. For this they conducted experiments on various building shapes such as rectangular, cross shape, cut shape, T shape, H shape, U shape and L shape. Each of these forms was designed in 15 variations of compactness by varying the lengths and depths to achieve different compactness values.

To conduct the correlation analysis to derive the relation between compactness and energy consumption, they used the following ratios:

a) The inverse of relative compactness

i.e. RC = A/V (Reference form) / A/V (Proposed form)

b) Energy consumption (Proposed form)/ Energy consumption (Reference form).

The results of the analysis (**Fig 2.13**) indicate that as RC increased, Energy consumption decreased. This result was in harmony with all the forms examined.

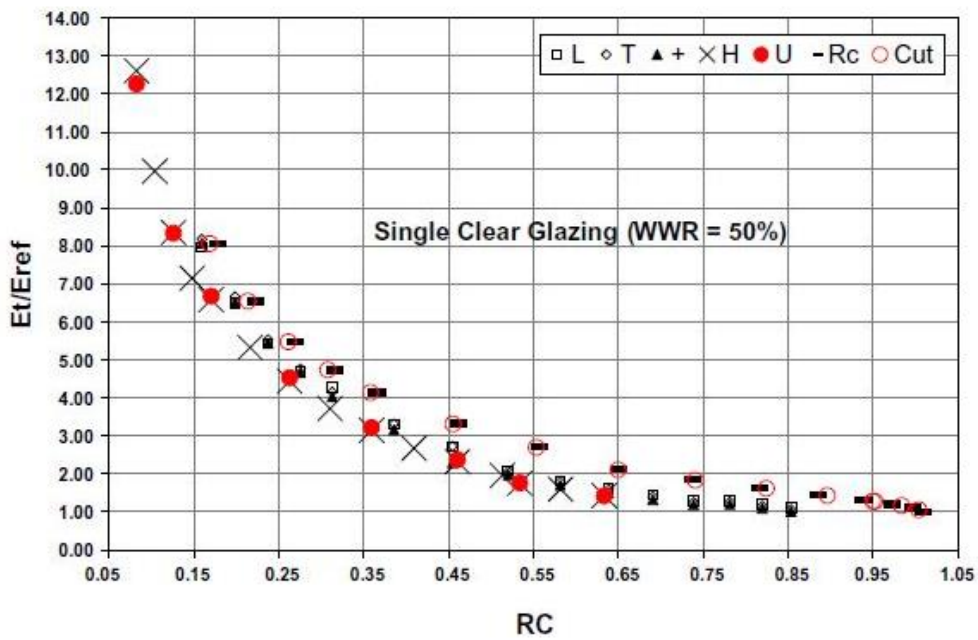


Figure 2.13 Correlation analysis; RC vs Energy consumption [37]

The results also indicate that compactness was significantly affected by the exposed surface area and thereby is a major determinant in calculating compactness.

Hamdan Ahmed [38] conducted a study in Malaysia to compare how different building forms and their vertical /horizontal spread will influence the total incident solar radiation. He compared a square vertical built form with a medium-rise horizontal built form and concluded that a vertical built form would receive 14.6% more solar radiation as compared to a low-rise building. He further concluded that a high-rise would receive 83.6% of total radiation from its vertical surfaces such as walls and windows while a medium-rise received 51.9% of total radiation from horizontal surfaces thereby being the most critical surface for heat transfer. For high-rise buildings, wall and windows serve to be the most critical surfaces.

Stark et.al [39] conducted a study on various 3 dimensional shapes to determine the exterior surface area exposure of various forms when volume is kept the same. Their results are presented in **Fig 2.14** stating a semispherical form has the least surface area exposure.

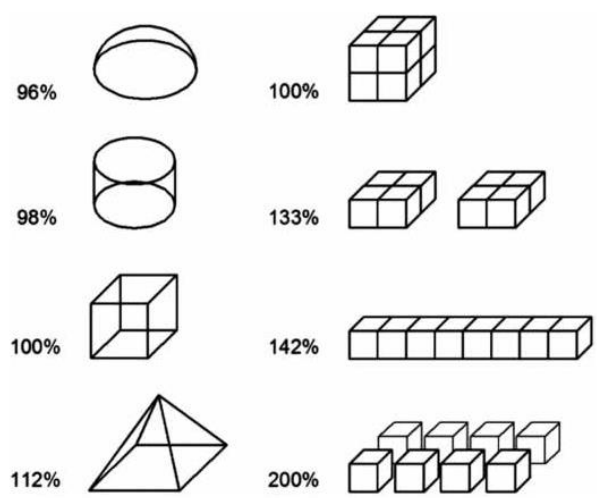


Figure 2.14 Forms with their surface area exposure [39]

2.5.3 Duration of shading/exposure

Muhaisen (2013) conducted a study on various geometric building forms with varying compactness ratio (Surface area/volume) to analyze the parameters that affect the energy efficiency in a Mediterranean climate. He first compared compact forms such as circular, square, octagon, heptagon and convex forms such as H shape, T shape, Cross shape and U shape. He found that the convex forms such as L, U and T increase cooling loads by 25.2%, 46.6% and 52.3% respectively.

He then investigated the "self-shading" parameters that impact the performance of the convex forms, by keeping (S/V) constant and varying geometric ratios such as building's roof / wall ratio and the building's depth ratio i.e. the ratio of exposed façade / the shaded façade (**Fig2.15**).

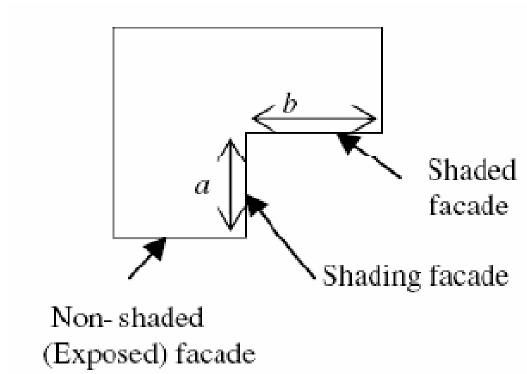


Figure 2.15 Building's depth ratio[40]

The roof/wall ratios varied between 0.1 - 0.5 – 1 and the depth ratio varied from 0.1 – 0.5 – 1 (**fig2.16**).

The results indicate that increase in depth ratio increases the percentage of shaded façade area and thereby reduce cooling loads. This phenomenon is also dependent on the roof/wall ratio; smaller the roof/wall ratio, higher will be the impact of depth ratio.

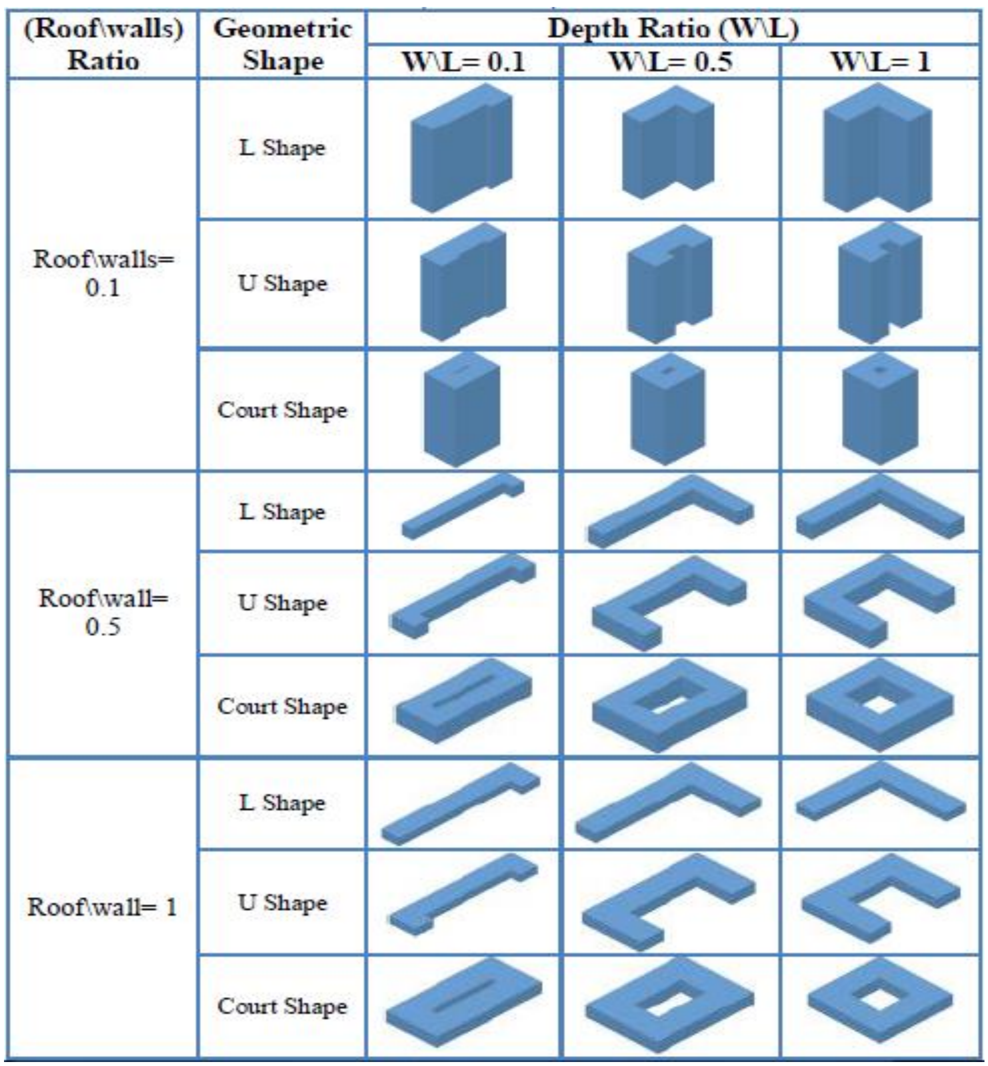


Figure 2.16 Studied forms and their geometric ratios [40]

Another important finding was that the impact of depth ratio varies from shape to shape. For instance the impact of increasing the depth ratio was negligible in an : "L" shape building, while increasing depth ratio from 0.1 to 0.5 for a "U" shape building; with the roof/ wall ratio as 0.1 help reduce cooling loads by 16.6%. This can be attributed to the form of the building itself. A “U” shaped building has 2 shaded facades which help reduce cooling loads, while the “L” shape building has just 1.

The Roof/wall ratio has also a significant impact. Increasing the roof/ wall ratio decreased the cooling loads.

Further experiments revealed that the “court shape” building amongst the convex forms is the most energy efficient for by reducing energy requirements by 15.4% as compared to a “U” shaped building.

2.6 Case studies - Form based buildings

2.6.1 Case study 1 - Shoali plaza, Riyadh

- Project status – Under construction
- Consultant – Greenhilli
- Project Concept – Minimizing solar heat gain by building form
- Project Description – The 25 story boutique office tower is located in Riyadh city.

The 25 story office tower is a prime example that considers solar heat gain as a chief contributor to cooling load and utilizes the form and mass to reduce its impact.

Each of the 2 stories is considered as a unit in odd and even sequence. Even units are bent from the Centre and surfaces are stretched out to maximize the glazing area towards the north. The odd units cantilever out of the even units to provide shading to even units

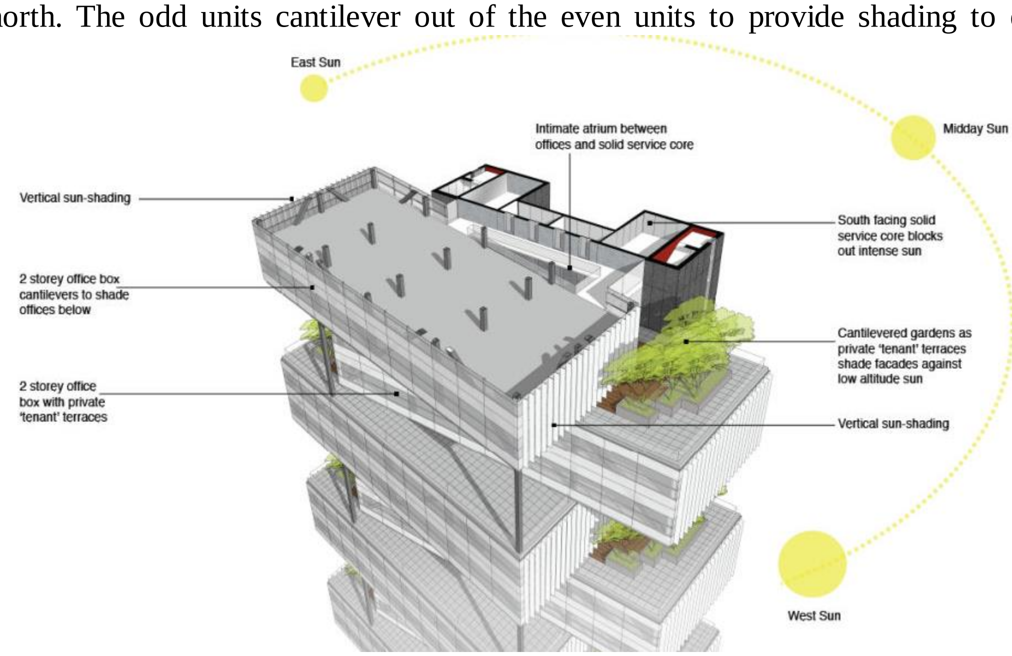


Figure 2.17 Solar Path and Building form in accordance [41]

The east and west elevation are shaded from low sun altitude through landscape placed on stretched out terraces and vertical shading devices. The core is completely shifted towards the south to minimize the intense heat gain through it (**Fig 2.18**)[41].

Figure 2.18 North elevation (a) and south elevation (b) of the Shoali Plaza [41]

2.6.2 Case study 2 -Cayan tower – Dubai

- Project status – Completed
- Consultant – SOM
- Project concept – A cuboidal form which is twisted from top and bottom.
- Project Description – Located in Dubai marina, the 306m tower is a residential building developed by a Saudi based developer. It accommodated about 500 apartments.

Figure 2.19 Elevation and facade details of the Cayan Tower [42]

The Cayan tower in Dubai is a chief example of form based energy reduction. Each floor is rotated about 1.2 degrees from the floor below to create a form that has taken a 90^{o} twist (**Fig 2.17**). The twisted form enhances the indoor comfort by ensuring self-shading from solar exposure for most of the interior spaces. The solar radiation is further deduced by recessed window sills, high performance glazing (which also reduce glare and provide diffused daylighting), metal cladded façade and exterior terraces. The result of the combination of these elements deduces the overall demand for cooling.

The form is also able to improve the indoor environmental quality as compared to a rectilinear building by shielding the northerly winds that carry fine particles of sand and dust. The building also utilizes cool winds during the night that blow in east-west direction to dissipate the heat absorbed by towers exposed slab thereby cooling down the thermal mass [42][43].

2.6.3 Case study 3 – Hamra Firdous tower, Kuwait

- Project status – Completed
- Consultant – Skidmore Owings And Merrill
- Project Concept – Designing an iconic form that takes into account local climatic condition such as sun and wind.
- Project Description – The tower is the highest skyscraper in the city of Kuwait soaring a height of 412m.

Figure 2.20 Hamra firdous tower - Shading effect of flair walls [44]

The iconic tower is glazed on three orientations and has a concrete wall in the south; finished in stone. Two flair walls run 130° around the building in opposite directions that appear as a wavy coat. Keeping the position of the summer sun in mind, the flair walls serve as shading devices by protecting the south façade from the harsh sun, thereby minimizing solar heat gain (**Fig 2.20**). The spiral appearing geometry was created by elimination of a quadrant from each floor plate and incrementally rotating the eliminated portion at higher levels; starting from south west at the bottom and ending at south east at the apex of the tower (**Fig 2.21**). The south wall is further composed of punched windows that allow daylighting and maximize views while still protecting from the high altitude sun. [45][46]

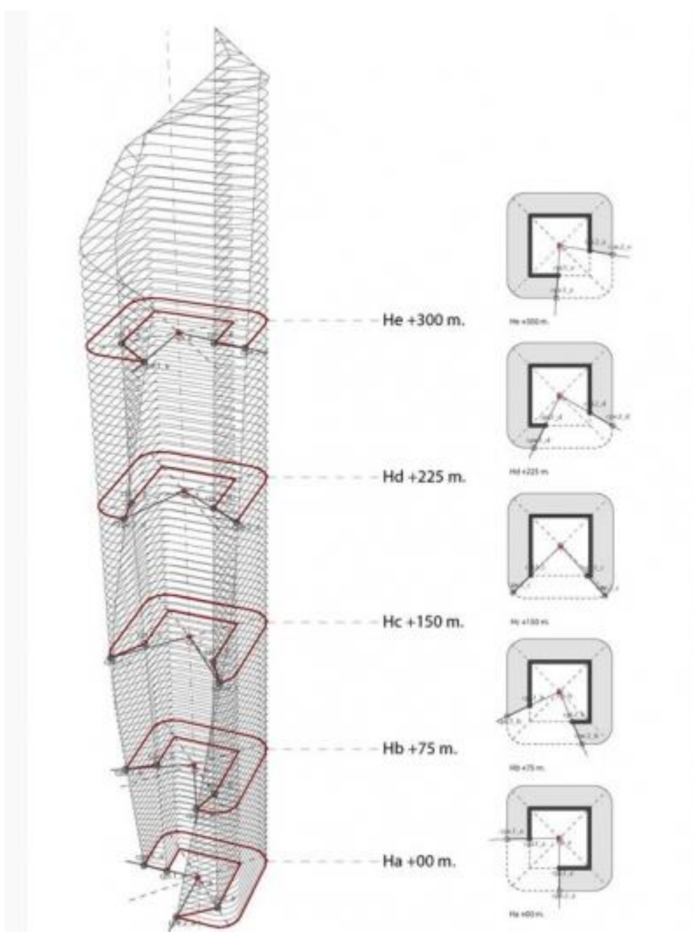


Figure 2.21 Elimination of floor quadrants to achieve flair wall design [45]

2.6.4 Case study 4 – Tencent seafront headquarters,Shenzhen, China

- Project status – Topped out
- Consultant – NBBJ
- Project Concept – Providing value associated with a high rise tower with connectivity of low rise building
- Project Description – The two towers are interconnected at different levels to ease work flow and house public amenities such as pantries, board rooms, auditoriums etc. The top of the tower is 250m high.

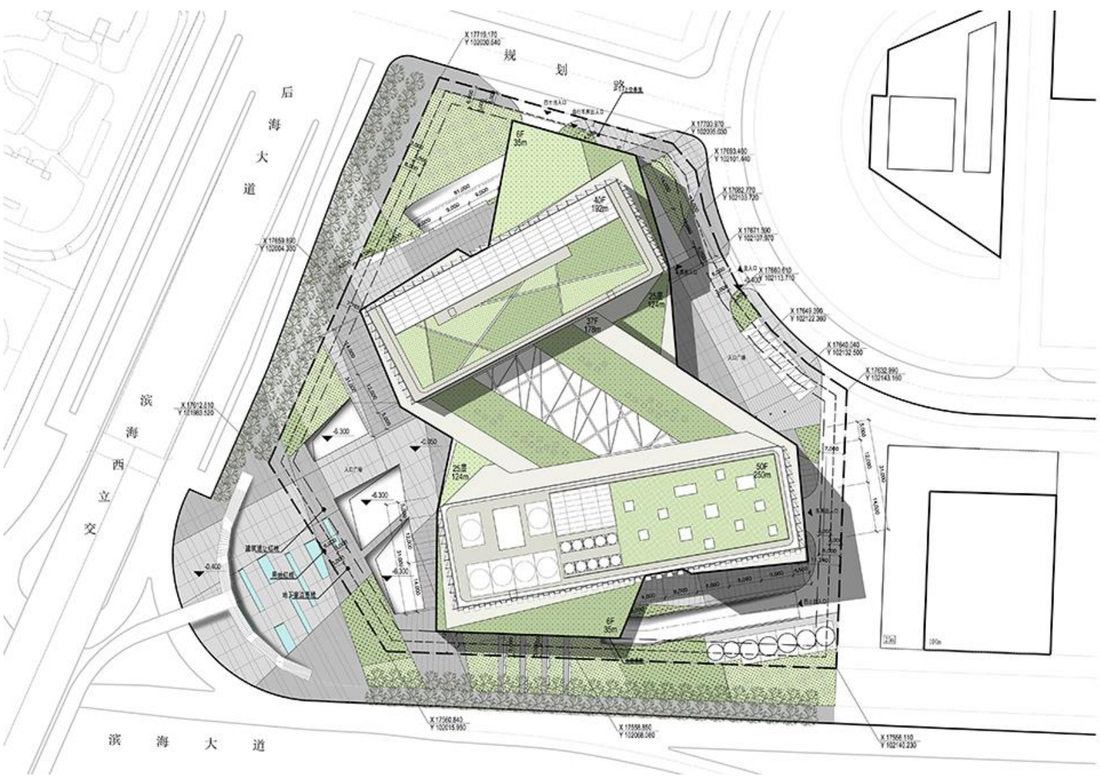


Figure 2.22 Site plan -Tencent Headquarters [47]

The tower was designed for Tencent which is a major web technology tycoon. Considering the hot and humid climate of southern China, the towers maximize passive energy efficiency strategies through proper orientation and rotation of the towers that minimizes exposure to direct sun and captures prevailing winds to keep the atria ventilated (**Fig 2.22**). Fins of varying lengths project over the glazing with widths of 0.9, 1.2 and 1.5m that help shade from the harsh sun (**Fig 2.23**), thus reduce the energy consumption by 30 percent as compared to a typical office tower. Other strategies including recycling of server generated heat to heat pools, kitchen and toilet water, live energy feeds etc.; help reduce energy consumption by a further 10 percent contributing to a total of 40% savings. The savings are equivalent to 1million US dollars annually [47-49].

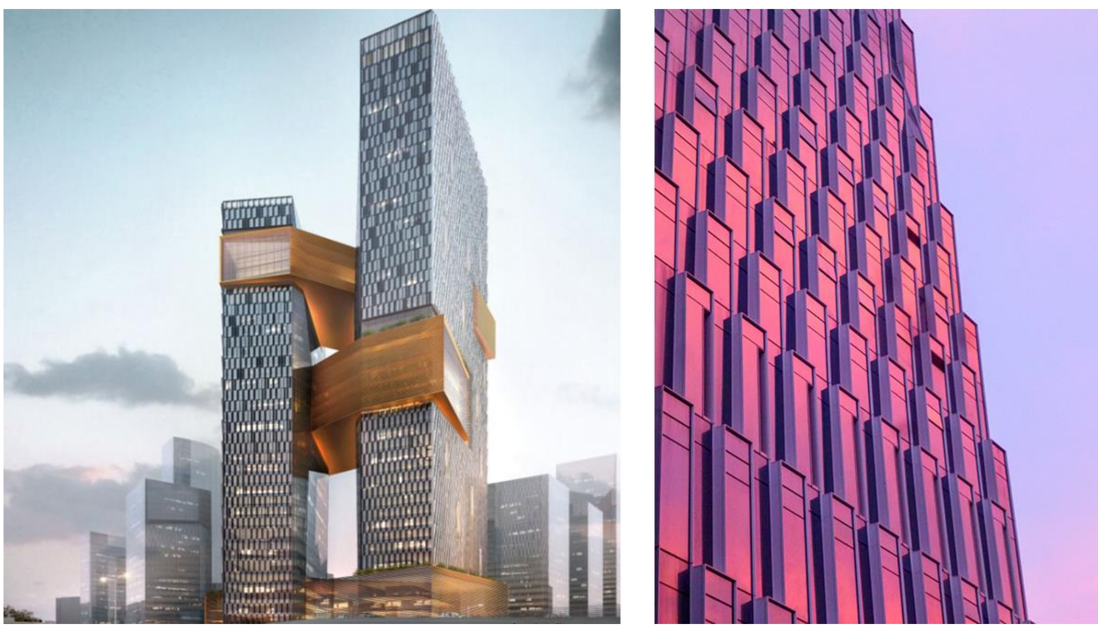


Figure 2.23 Form design and facade details - Tencent Headquarters [47]

2.6.5 Case study 5 – Absolute towers, Ontario, Canada

- Project status – Completed
- Consultant – MAD architects
- Project Concept – A soft organic form that revives metropolitan's desire towards nature.
- Project Description – The two apartment towers stand at 150 and 170m with floors in oval shape and rotate 1-8° as they go vertical.

Figure 2.24 Form of Absolute towers [52]

The absolute towers are a pair of residential towers in Ontario Canada. The floor plates are oval in shape and rotate 1-8° vertically, which gives a total rotation of 209°from top to bottom (**Fig 2.24**). This provides the tower with its distinct form. Solar passive strategies have been employed by provision of balconies that wrap around each floor which help provide shading from the high angle sun in summer and allow low altitude sun in winter (**Fig 2.25**). This helps the towers to reduce loads on the mechanical system. [51][52]

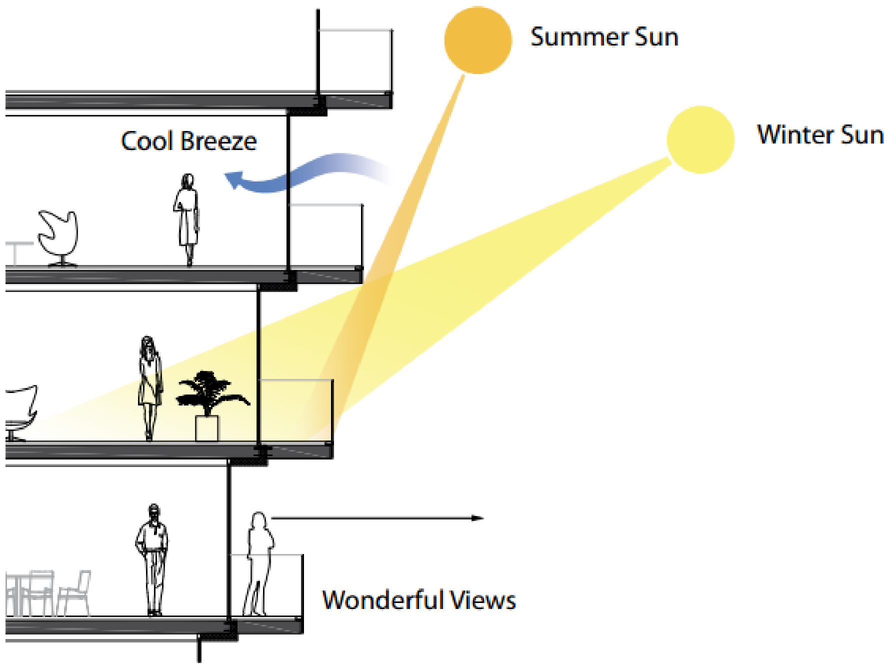


Figure 2.25 Sectional view of absolute towers [52]

2.6.6 Case study 6 – The Bow, Calgary

- Project status – Completed
- Consultant – Foster + Partners
- Project Concept – Designing an iconic form that takes into account local climatic condition such as sun and wind
- Project Description – The tower is the tallest commercial building in Calgary at 236m in height.

Figure 2.26 Form and façade details of The Bow [53]

The tower is considered an iconic example that responds to local climate and site constraints. As illustrated in **Fig 2.26**, the convex profile faces windward direction to minimize wind loads while the concave profile faces south to receive maximum solar radiation to combat the cold weather conditions of Calgary. The building in the south is pushed behind from the exterior glass curtain to create an atrium space that extends till the top (**Fig 2.27**). This atrium acts as climate buffer space and redistributes the heat throughout the building by means of attraction. These measures help to conserve energy by 30% [53][54].

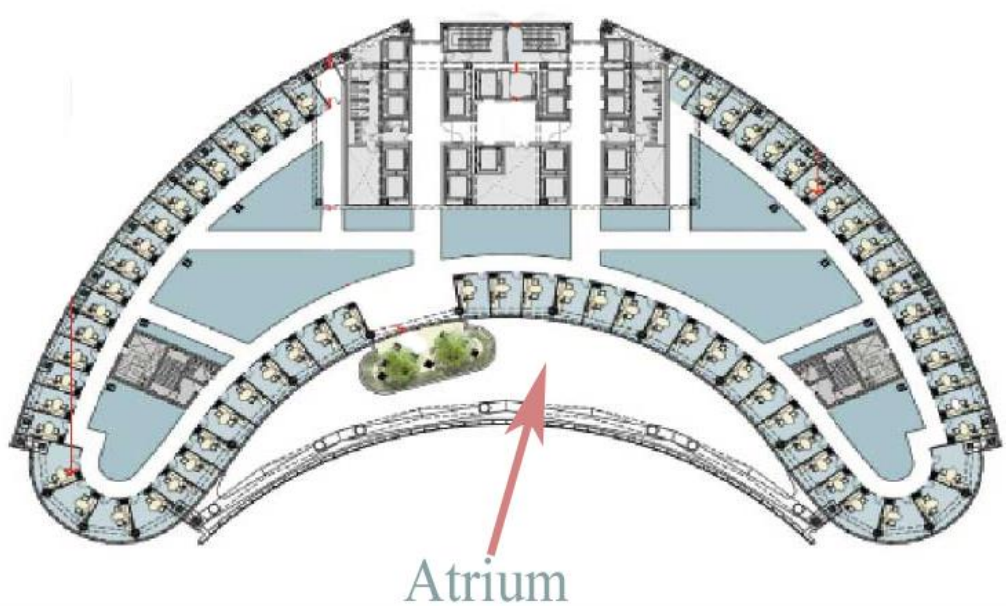


Figure 2.27 Ground floor plan showing the atrium space created south of the building [55]

2.6.7 Case study 7 –Diamond Building – Malaysia

- Project status – Completed
- Consultant – NR architect
- Project concept – Self shaded building to reduce solar heat gain by usage of tilted façade.
- Project Description – The Diamond building houses the Energy Commission's headquarters of Malaysia. The building exhibits technologies to minimize energy consumption and usage of potable water, foster sustainable building materials and imparting enriched indoor environmental quality.

Figure 2.28 Outward tilted facade of diamond building [56]

The design of the building is in consonance with Malaysia's hot humid climate and integrates ideas and concepts for a sustainable building, thereby placing the comfort of occupants at priority. As shown in **Fig 2.28**, the tilted façade of the building allows self-shading for the lower floors, thereby protecting from direct sun rays into the building. Another advantage of this design is its small building footprint, allowing landscaping around the site which in turn reduces the reflective heat transfer from the ground. The façade also integrates light shelves that admit natural daylight deep into the space and placing lesser loads on the buildings lighting system [57].

2.7 Simulation software investigation

BPS tools (Building Performance Simulation) prove to be valuable tools in a range of applications including energy saving potential in initial design stage, existing buildings, retrofitting solutions, fault detection and diagnosis etc. [58].

A great number of BPS tools to predict energy performance of buildings exist. Each of these softwares has their own distinctive features in terms of modeling, user interface, solution algorithms, modeling options etc. Although these tools receive updates on a regular basis and have active communities for development and enhancement of modeling capabilities, their software architecture and concepts do not change [57]. The 3d modeling capabilities thereby are restricted to model static forms with lesser flexibility for nonstatic forms. The present literature available regarding approaches in modeling and concerns related to simulation of nonstatic forms is fragmented. Simulation users thereby have to develop their own strategies [59].

One of the current trends in modeling and simulation involves segregation of these activities into different softwares. As illustrated in **Fig 2.29,** the building geometry is modeled in a 3d modeling software that supports exporting to gbXML format.While some softwares allow direct exporting, other modeling softwares are dependent on intermediate plugins for conversion. This file is then imported in compatible simulation software for analysis [60].

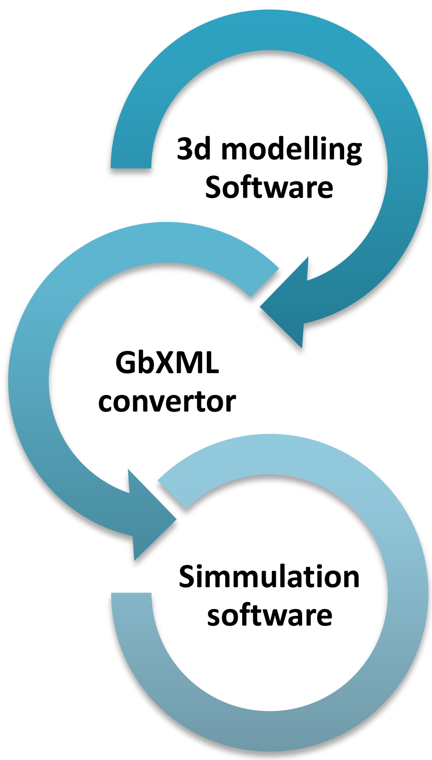


Figure 2.29 Schematic workflow of energy simulation

2.7.1 Choosing the 3D modeling software

While conducting energy simulation, it is necessary to model the building to a certain level of detail, exceeding which the simulation software would not respond [61].

The American Institute of Architects documented levels of design (LOD) ranging from LOD 100-500.

LOD 100 - Pre-design phase which presents general mass.

LOD 200 – Includes details in the mass such as ceilings, floors, walls, openings in walls for windows and doors.

LOD300 - Construction documents.

LOD 400 - Shop and fabrication documents.

LOD 500 - Digital representation of the final design.

In most of the cases, LOD 200 is sufficient to determine energy demand of the building.

The basic criteria therefore for choosing modeling software are:

- Model various building forms with flexibility.
- Allow exporting geometry to simulation software.

Trimble SketchUp and Autodesk Revit are the modeling softwares that are used extensively with capabilities to export 3d geometry to energy simulation software [62].

Spencer (2013) Conducted study on energy modeling methods for commercial buildings. For this models were created in Autodesk Revit and gbXML format was exported to green building studio. Five common errors occurred while importing gbXML files in Green

Building Studio. These errors included: “exceeding DOE 2.2 limits”, “Invalid gbXML file” etc. Out of 35 models that were to be tested, only 6 were able to exported and tested.

With the help of numerous modeling plugins, Sketchup shows more flexibility in modeling complex geometry with the required level of detail. The gModeller plugin helps create thermal zones and export gbXML files which can then be imported in a gbXML compatible tool such as gEnergy or EnergyPlus for further processing. The plugin also simplifies the process of energy analysis and facilitates early stage "what-if" scenarios, thereby making SketchUp a smart solution for low carbon building design [64].

2.7.2 Choosing simulation software

Atia et.al (2009) study compared top ten different BPS tools screened by Department of Energy Directory which included Design Builder, Green Building Studio, DOE-2, eQUEST, ECOTECT, Energyplus, Energyplus Sketchup (open studio), HEED, Energy 10 and IES VE. They collected 249 survey responses from architects, designers and professionals.

The results show that Ecotect, DesignBuilder, Green building studio and Energy10 bear friendly user interfaces but portray difficulty in integrating the tools with architectural design process.

IES VE did not possess ease in learnability, whereas HEED and DOE 2 did not contain their own weather data and an extensive library of building components.

eQuest is constrained when it comes to non-conventional building components while open studio is limited to fairly simple geometry.

Another study [65] listed merits and demerits of Ecotect. Though the software is flexible in terms of geometry that can be simulated and graphically show thermal response of building skin, it is unable to:

- Simulate the dynamic nature of a building’s thermal performance.
- Consider the impact of solar radiation as it penetrates the space. It considers solar radiation as a space load at the window exterior surface itself.
- Calculate thermal lag for composite elements which are not contained in its library.

Crawley et al. [66] conducted studies for validation of the most powerful simulation tools which included EnergyPlus, TRNSYS , IES VE , ESP-r, and ICE.

As indicated in **Table 2-2**, the results show that Energy plus, ESP-r and TRNSYS are the most comprehensive software. However TRNSYS does not support import/export of geometry and ESP-r does not support solar analysis which is an integral part of the study.

Hence Energy plus proves to be a viable option in conducting energy simulation. Energy plus is also the considered the most powerful simulation tool with design builder as its supporting user interface.

Also since the study deals with interaction of the building’s morphology with solar radiation, Ecotect was used as secondary software to obtain the thermal response of building’s skin.

Table 2-2 Comparison of simulation softwares [66].

	Energy Plus	ESP-r	IDA ICE	IES	TRNSYS
Simulation Solution					
Simulation of loads, systems and solutions	X	X	X	X	X
Iterative solution of nonlinear systems	X	X	X	X	X
Duration of Time Calculation					
Variable time intervals per zone for interaction of the HVAC system	X	X			
Simultaneous selection of building systems and user		X	X	X	X
Dynamic variables based in transient solutions	X	X	X		
Complete Geometric Description					
Walls, roofs and floors	X	X	X	X	X
Windows, skylights, doors and external coatings	X	X	X	X	X
Polygons with many faces	X	X	X	X	
Imports of building from CAD programs	X	X	X	X	X
Export Geometry of Buildings for CAD software	X	X	X		
Import / Export of simulation models of programs	X	X	X	X	
Calculation of thermal balance	X	X	X	X	X
Absorption / release of moisture from the building materials	X		X	X	X
Internal thermal mass	X	X	X	X	X
Human thermal comfort	X	X	X	X	X
Solar Analysis	X				X
Analysis of Isolation	X	X	X	X	X
Advanced fenestration	X	X	X	X	X
Calculations of the building in general	X	X		X	X
Surface temperatures of zones	X	X	X	X	X
Airflow through the windows	X	X		X	X
Driving surfaces	X	X	X	X	X
Heat transfer from the soil	X	X	X	X	X
Thermophysical variable			X		
Daylighting and lighting controls	X	X	X	X	
Infiltration of a zone	X	X	X	X	X
Automatic calculation of coefficients of wind pressure				X	
Natural Ventilation	X	X	X		X
Natural and mechanical ventilation				X	X
Control open of windows for natural ventilation	X	X	X		X
Air leaks in multiple zones	X	X	X		X
Renewable Energy Systems					
Solar Energy	X	X		X	X
Trombe Wall	X	X	X	X	X
Photovoltaic panels	X	X		X	X
Hydrogen Systems		X			X
Wind Energy		X			X
Electrical Systems and Equipment					
Energy Production through R.E.	X	X			X
Distribution and management of electric power loads	X	X			X
Electricity generators	X				X
Network connection	X	X			X
HVAC Systems					
HVAC idealized	X	X	X	X	X
Possible configuration of HVAC systems	X	X	X	X	X
Repetitions cycle air	X	X	X	X	X
distribution systems	X	X	X	X	X
Modeling CO_2			X	X	X
Each distribution of air per area	X	X	X	X	X
Forced air unit per zone	X	X	X	X	X
Equipment Unit	X	X		X	X

CHAPTER 3

MODELING BUILDING FORMS

3.1 Creation of base case

In order to evaluate the performance of a contemporary form and to scrutinize the parameters that influence energy conservation and heat gain, a static reference building is necessary to be modeled and compared to. The base case should be generated of good energy practice and as well follow current architectural trends in aesthetics, so as to set the right benchmark for other building forms. To develop the base case, the following building aspects were studied:

3.1.1 Aspect ratio

A study compares cuboidal and cylindrical building forms in terms of the aspect ratio to analyze its impact on energy consumption. It was found that buildings with aspect ratio 1:1 receive the lowest solar insolation thereby being the most energy efficient forms in hot climates [38]. Therefore the study chooses a Simple Cuboidal form as the base case with the floor plan in the aspect ratio 1:1. Not only does this aspect ratio have an influence on energy consumption, it also justifies the building in all orientations, thereby directing the focus of the study on form based parameters.

3.1.2 Building areas

Based on a survey, a typical office building in KSA occupies 300-800m^2 of gross floor area [67]. This study thereby choses 625 m^2 as a standard occupiable floor area. Since a high rise building is defined as the one that exceeds 7 floors or 23m in total height [68], the base case was considered to have 19 floors. The individual floor height was assigned to be 4.5m, thereby making the total height as 85.5m.

3.1.3 Thermal zoning

Considering that there are diverse forms that will be modeled and simulated, employing a common structural system to all forms is unfeasible practically. Moreover certain modeling complexities may arise when assigning a common structural core to all building forms.

Considering a standard cuboidal core assigned to all building forms, certain complexities may arise such as:

- In case of a twisted building form, the core may get twisted along with the building during modeling stage. Even if this issue is resolved by redesigning the core to follow a static linear path, it creates improper division of zones due to changing geometry of every floor.

Thereby to achieve neutral zoning in all buildings, a straight line axis is used in the center instead of a core thereby creating four equal thermal zones using 45^o lines from central axis.

3.1.4 Construction modules

The base case incorporates thermal characteristics of building envelope components such as Roof, floors, slab on grade, fenestration as recommended by ASHRAE 90.1-2016. However, to meet the architectural trends of using fully glazed system in office buildings, the glazing was modified from recommended 40% glazing to 100% glazing.

3.1.5 HVAC and Lighting

Recessed fluorescent lamps with linear control are chosen as general lighting for the building. Each zone has two light sensors placed; one covering 70% of the zone area and the remaining 30% in the interior area of the zone. The target luminance was set as 500 lux. Apart from general lighting, task lighting is also provided that operates with occupancy.

To choose the most energy efficient HVAC system, an optimization was conducted on different VAV and VRF systems. It was found out that VRF systems consume 34% lesser energy than conventional VAV systems and hence was chosen for modeling.

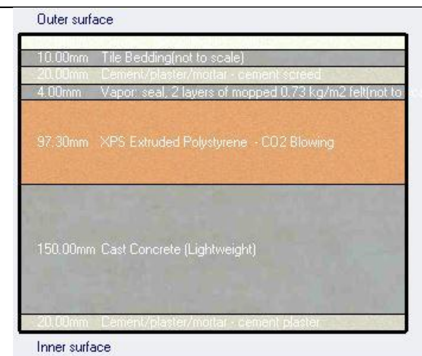
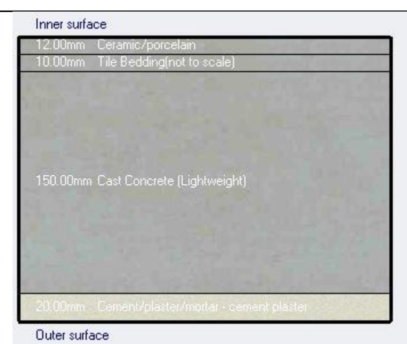
Summary of the building model characteristics are specified in **Table 3-1**.

3.1.6 Operation Schedules

The working schedule for the office building has been set from Saturday-Thursday with work timings from 8am-6pm representing typical working hours in Saudi Arabia. The annual holidays are assigned to be 20 days based on the latest gathered data [69]. The occupancy profile has been assigned considering the presence of maintenance staff prior and post occupancy. It is also assumed that 50% of the regular staff will not be occupying the building during lunch hours i.e. 11am-12pm. The task lighting schedule is in accordance with the occupancy of the regular staff, while the general lighting schedule is assigned in accordance to maintenance staff. The HVAC schedule is assigned in a step manner such that it initiates two hours before occupancy and shuts two hours post occupancy.

Summary of the Operation schedules is specified in **Table 3-2**

Table 3-1 The base case Model specifications/characteristics

<table>
<tr><th colspan="2">Input Category</th><th colspan="2">Input Description</th></tr>
<tr><td rowspan="7">GENERAL</td><td>Location</td><td colspan="2">Riyadh, Saudi Arabia</td></tr>
<tr><td>Building orientation</td><td colspan="2">Justified in all (aspect ratio 1:1)</td></tr>
<tr><td>Floor height</td><td colspan="2">4.5m</td></tr>
<tr><td>Total Number of floors</td><td colspan="2">19</td></tr>
<tr><td>Gross floor area</td><td colspan="2">11875 m^2</td></tr>
<tr><td>Occupancy density</td><td colspan="2">1person/11m^2</td></tr>
<tr><td>Occupational period</td><td colspan="2">8:00am-6:00pm (6days a week)</td></tr>
<tr><td rowspan="3">ENVELOPE</td><td>Exterior wall</td><td>U-Value
3.292 W/m^2.K</td><td>
</td></tr>
<tr><td>Roof</td><td>U-Value
0.273 W/m^2.K</td><td>
</td></tr>
<tr><td>Floor</td><td>U-Value
1.40 W/m^2.K</td><td>
</td></tr>
</table>

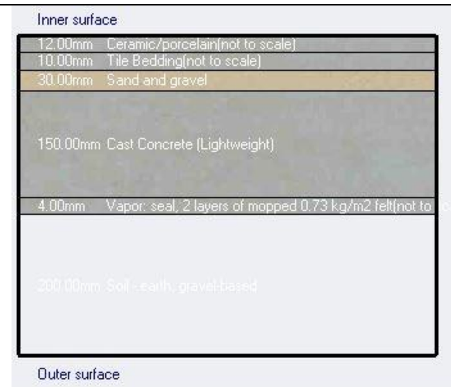
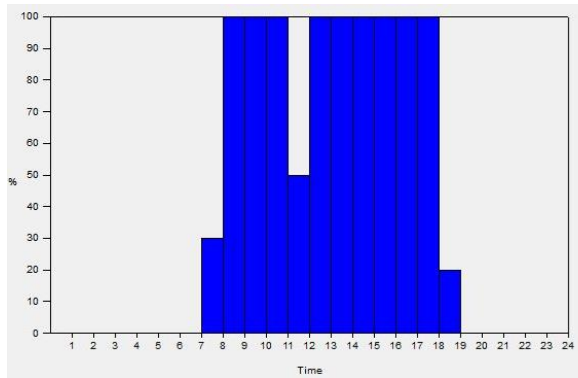
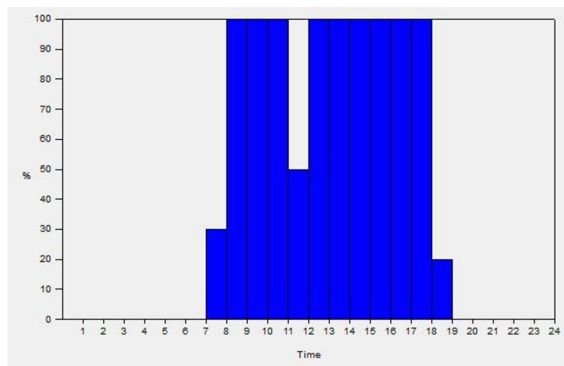
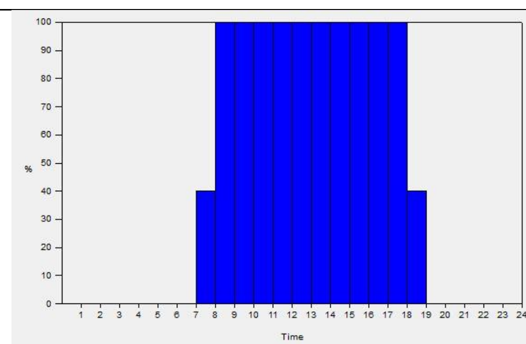
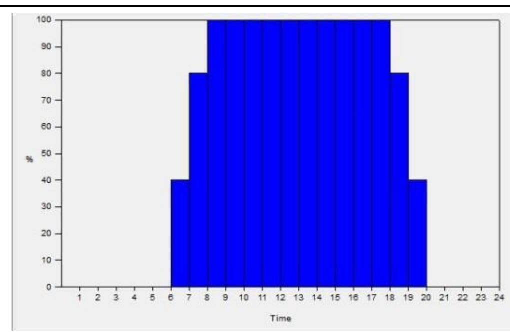
ENVELOPE	Slab on grade	**U-Value** 0.81 W/m^2.K	
	Window to wall ratio	100%	
	Air leakage rate	0.05 ac/h	
	SHGC	0.621	
	VT	0.743	
	Window U value (Fixed)	3.23 W/m^2.K	
HVAC	System type	VRF	
	Cooling Setpoint/Cooling Setback	25^{o}C/28^{o}C	
	Heating setpoint	20^{o}C	
LIGHTING	Luminaire Type	Recessed	
	Lighting Power Density	3.5 W/m^2-100lux	
	Target Illumination	500 lux	
	Lighting Control	Linear	
OTHERS	Computer gains and equipment gains	11.7 W/m^2	
	Activity level	0.9(Light office work)	
	Annual holidays	19 days(Religious)	
	Simulation period	One Year	

Table 3-2 Occupancy profiles

S.No	Type	Profile
1.	Occupancy Profile	
2.	Task Lighting	
3.	General Lighting	
4.	HVAC	

3.2 Choosing the case study forms

While numerous possibilities exist to generate contemporary forms, it was an ideal decision to create geometries similar to existing high rise contemporary forms. For this reason, an online survey was conducted to examine some of the existing forms. The main criteria in choosing these forms are:

- Justification in all orientations: Forms that could be modeled with a footprint in the aspect ratio 1:1.
- All cardinal elevations having the same geometry: To be unbiased in terms of surface area exposure and façade properties in all elevations.

Considering that various forms will be examined, there is a possibility of the floor geometry and proportions changing from floor to floor. To make the comparison unbiased, forms were modeled by setting baselines. These are:

- Assigning all modules such as envelope, lighting and HVAC as base case.
- Fixing the ground coverage area for all models (625sqm).
- Fixing the gross occupiable area for the floors combined (11875sqm).
- Fixing the overall building height (85.5m) and individual floor height (4.5m).

Based on the judging criteria, the following case studies were chosen for modeling and simulation and graphically illustrated in **Table 3-3**:

3.2.1 Case study Form “B”: Simple Curvilinear

Since curvilinear are one of the most emerging forms [7], a simple curvilinear form was chosen and modeled with the same floor area as base case. The form was inspired from the Westhafen Tower in Frankfurt. Since circles are represented using a number of straight edges in modeling software, this form was created using 32 edges for the circular floor plan. The floor plan was repeated in parallel to create a cylindrical geometry (fig 2b, 2c).

3.2.2 Case study Form “C”: 90^0 twisted building

Inspired by the Majdoul tower in Riyadh, which twists at an angle of 90^0 from the base, Form C was modeled with a base of 25m x 25m and twisted smoothly at 90^0 using the SketchUp plugin “fredoscale”. As a result each vertical façade had been subdivided into two triangles which tilted at $+13^o$ and -13^o to create the “twisted” effect. (fig 3b) The triangles inclined at -13^o protruded out of the vertical facade, thereby surrounding the form in a circular pattern in the top view (fig 3c).

3.2.3 Case Study Form “D”: Staggered twisting

Inspired by the F & F tower in Panama City, that uses staggered twisting (i.e. Floors twisting as individual blocks), Form D was modeled with individual floor rotation as 5^0 creating an overall rotation of 90^0 (fig 4b). The rotated overlapping of floor blocks resulted in exposition of portion of floors and portions of roofs in every block in all directions. The extra exposed roof elements surround the form in a circular manner similar to Form C (fig 4c).

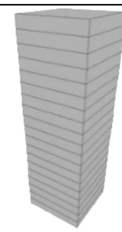
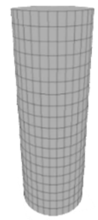
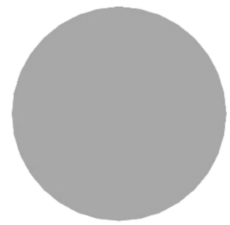
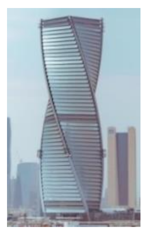
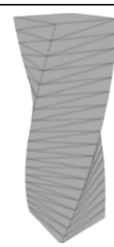
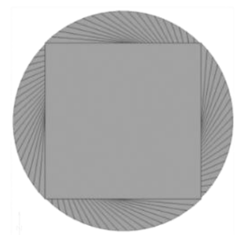
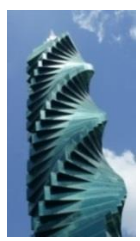
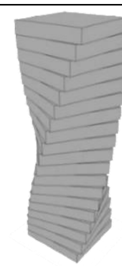
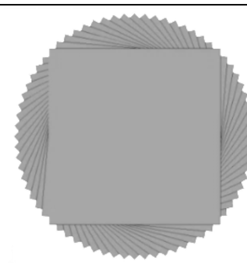
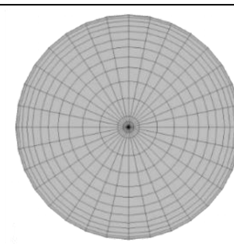
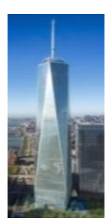
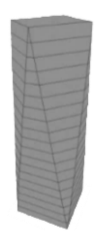
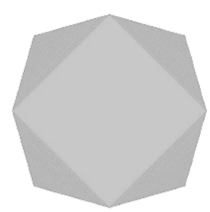
3.2.4 Case Study Form "E": Curvilinear tordos

Inspired by the famous Gherkin in London, Form E was modeled using a similar bulge to the former to create a curvilinear-bulged-tapered building. The floor area differed from floor as a result of the geometry, but the overall occupiable area was set based on previously mentioned guidelines. Similar to Form B, the circular floor plans were generated using 32 edges. As a result of the bulging and tapering, the roof element was created in unison with vertical glazing i.e. a flat roof didn't exist and the glazing continued to form the roof (fig 5b).

3.2.5 Case Study Form "E": Crystalline twisting

Inspired by the One World Trade Centre in New York, Form E was modeled by creating a floor plate 25m x 25m at the base, and a roof 21.7m x 21.7m which was rotated at 45^o .The floor base and roof top were connected through by joining the vertex of the roof with two adjacent vertices of the floor. This was repeated in all orientations to create the form (fig 6b). The form hence created 8 large triangles, 4 of which were tapered 2^o inside while the remaining four were tapered 4.5^o outside. The inside outside tapering created the intermediate floor plates to take an octagonal shape.

Table 3-3 The Case study forms

	S.no	Designation	Existing building form (a)	Created geometry perspective (b)	Created geometry top view (c)
BASE CASE	1.	Form "A"	--------		
CASE STUDY – 1	2.	Form "B"			
CASE STUDY – 2	3.	Form"C"			
CASE STUDY – 3	4.	Form"D"			
CASE STUDY – 4	5.	Form "E"			
CASE STUDY – 5	6.	Form "F"			

3.3 Modeling work flow

All the chosen case studies and base case buildings were modeled using Trimble SketchUp. The software has a comparative advantage over other modeling software in terms of its flexibility on modeling forms and its interconnection with other programs. Since there were two different simulation softwares to be used i.e. Design builder and Ecotect, The approach in creating compatible models for both softwares was different.

3.3.1 Path 1: For Design Builder

Step 1-Basic Modeling: To make a model export compatible, it has to be modeled in "paper" thickness i.e. the exterior and interior surfaces of the model have no specific thickness. Later on when these models are taken into design builder, the thicknesses of the materials such as roofs, glazing etc. can be assigned. Hence observing the case studies in table 3-3 section a, and confining to the baselines provided in section 3.2, the six building geometries were modeled in "paper" thickness.

Step 2-Surface assignment: Using the Plugin "Gmodeller", Surfaces were assigned as walls, roofs, internal floors, internal partitions etc. This is the second essential step to make the model export compatible since these surfaces will be identified by design builder by their corresponding allotment. However, Gmodeller does not apply the "window" material to any vertical surface that is not at right angles with the base. So for any surface that is tapered or inclined, it exports it as an opaque exterior wall. This can however be rectified in design builder by manually drawing windows over each designated surface.

Step 3-Zone creation: Using gmodeller, zones were assigned based on the modeling surface divisions. Some basic rules to be followed while creating a zone using G modeler are as follows:

- The anticipated zone must be closed manifold. i.e. it must not have holes or unconnected edges and vertices.
- A zone is created when it is bound by: A floor surface, a roof Surface, External walls and internal partitions (if any).
- No two spaces can share a common external wall
- No internal floor/partition can be shared by more than two adjacent zones

Step 4-Exporting Gbxml file: The analysis section in gmodeller helped to ensure that all the above conditions were met and there were no errors in modeling, surface assignment and zone creation. Once the zero error report was generated, the buildings were then exported into "gbxml" files which were imported in Design builder using the "import BIM" dialogue.

Step 5-Adding modules for Energy Plus: Using Design builder, windows were manually drawn to each surface of the building. Though design builder has a module that automatically generates windows with the specified WWR, it had a similar issue to auto generate windows on non-right angled surfaces.

Other modules such as the envelope thermal properties, construction layers, lighting profile and lighting control, HVAC type and setpoints, Occupancy profiles and holidays etc. were added. The latest weather data file for the city of Riyadh generated for a typical year was used.

The model is now ready to be simulated in Energy plus to calculate the Annual Energy Consumption.

3.3.2 Path 2: For Autodesk Ecotect

Step 1-Basic Modeling: Modeling procedure For Ecotect is similar to the model preparation for Design Builder except for the number of elements. All internal partitions, floors were not modeled since Ecotect requires only the outer shell of the building for solar analysis.

Step 2-Exporting .3ds file: SketchUp by default has the capability of exporting .3ds file and thereby is not dependent on additional plugins such as gmodeller. Therefore a ".3ds" file was exported from SketchUp and imported in Ecotect.

Step 3-Fine tuning: To Conduct Solar analysis in Ecotect, it is necessary that all surface normal shall face outwards; hence each external surface was checked and reversed if required.

The model is now ready to conduct Solar access Analysis.

Fig 3.1 Graphically depicts the above mentioned workflow.

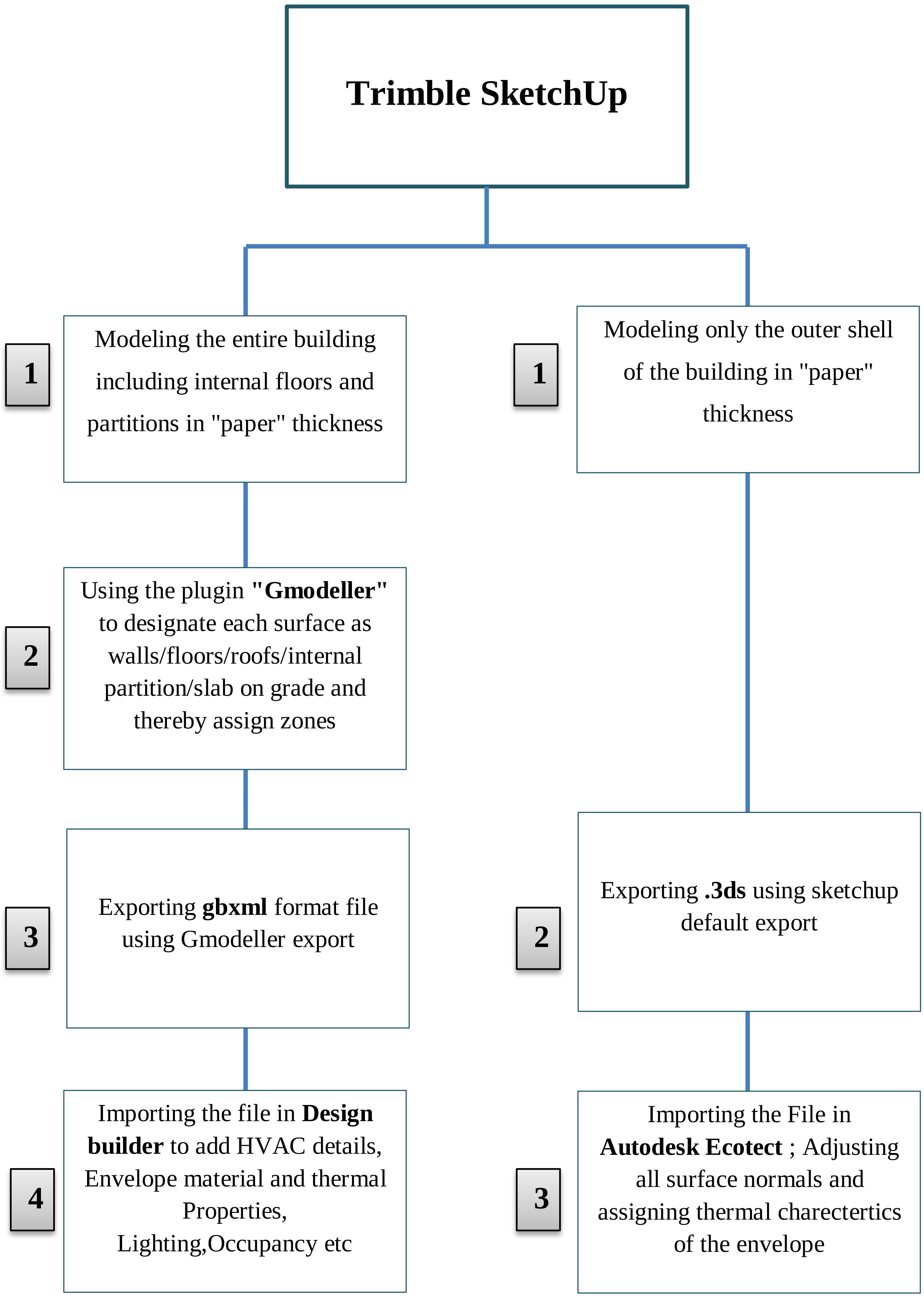


Figure 3.1 Modeling Workflow

CHAPTER 4

SIMULATION AND RESULTS

4.1 Preliminary simulation

Before proceeding with energy simulation of case study forms, a preliminary simulation was conducted to analyze the following:

a) Assessing the impact of window to wall ratio on energy consumption.

b) Assessing the impact of morphological "actions" on energy consumption

4.1.1 Window to wall ratio

As seen from literature, a trend towards fully glazed buildings in high rise sector has been witnessed. Before assessing the impact of building form on energy consumption, it is necessary to analyze the impact of WWR on heat gain and energy consumption. For this a static base case office building of cuboidal form was developed with a gross occupied area of 6000 m^2 spread in 15floors. This resulted in each floor containing 400 m^2 of office space which lies in the average of office space area in KSA. The construction profile and occupancy profile are in accordance with Tables 3.1 and 3.2.

The range of WWR analyzed were 40% (ASHRAE recommended), 60%, 80% and 100% (current trend).

Energy simulation was carried out on the static form with the specified WWR, which reveals that increase in WWR increases energy consumption by increasing cooling energy consumption. The energy consumption when WWR was 40% was found to be 149.8kWh/m^2/yr, at 60% was 162.9 kWh/m^2/yr, at 80% was 178.4 kWh/m^2/yr and at 100% was 190.9 kWh/m^2/yr. The difference in energy consumption from ASHRAE recommended value of 40% WWR to the current trend of 100% WWR was 27.4%.

Since the floor area for all the studies cases was the same, the general energy consumption remained the same. The lighting energy consumption varied to a maximum of 3% from the base case with 40%WWR to the case with 100%WWR as seen in **Fig 4.1 (a)**. This is as a result of low floor area which resulted better penetration of daylight. The cooling energy consumption as shown in **Fig 4.1 (b)** increased with the increase in WWR. The increase in cooling energy from the base case for WWR 60%, 80% and 100% were 14%, 30% and 43% respectively.

The solar heat gain through envelope was analyzed to examine influence on cooling energy. As seen from **Fig 4.2 (a)** , increase in heat gain through glazing increases with increase in WWR, while it decreases heat gain through opaque components such as walls and roofs as shown in **Fig 4.1(b)**.

The studied case with 100% WWR increased solar heat gain through glazing by 149% while simultaneously reducing heat gain through opaque components by 99%.

The studied case with 80% WWR increased solar heat gain through glazing by 100% while simultaneously reducing heat gain through opaque components by 73.8%.

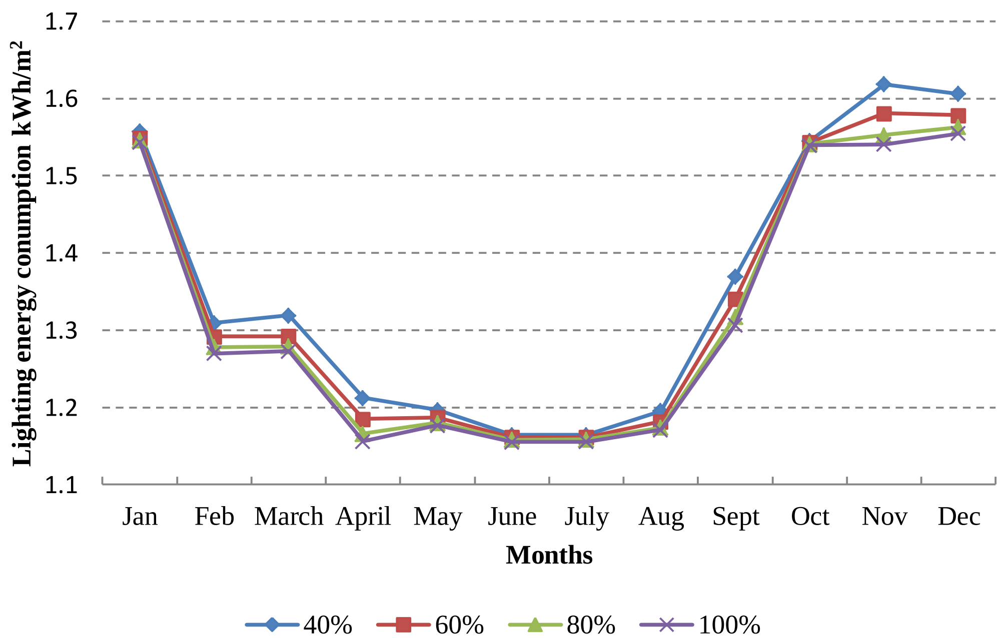
The studied case with 60% WWR increased solar heat gain through glazing by 44% while simultaneously reducing heat gain through opaque components by 40%.

Despite the decrease in heat gain through opaque components, the reduction in all the studied cases was not significant enough to offset heat gain through glazing and hence energy consumption increases. **Table 4-1** tabulates a percentage comparison of the studied WWR cases in terms of solar heat gain and Energy consumption with the base case of 40% WWR

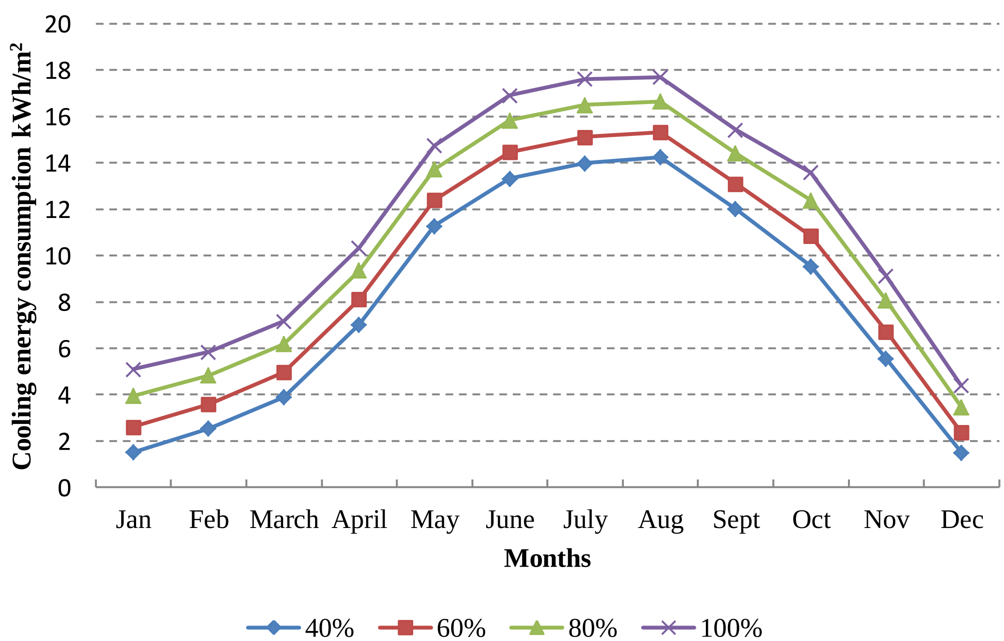
Table 4-1 Comparative summary of Solar heat gains and Energy consumption of studied WWR

WWR	60%	80%	100%
Annual Solar heat Gain-glazing	+44%	+100%	+149.6%
Annual Solar Heat Gain-Opaque surfaces	-40%	-73.8%	-99%
Annual Cooling Energy Consumption	+14%	+30%	+43%
Annual Lighting Energy Consumption	-1.3%	-2.2%	-3%
Total Annual Energy Consumption	+8.7%	+19.08%	+27.4%

Note: (-) indicates improvement (reduction in consumption (or) solar heat gain)



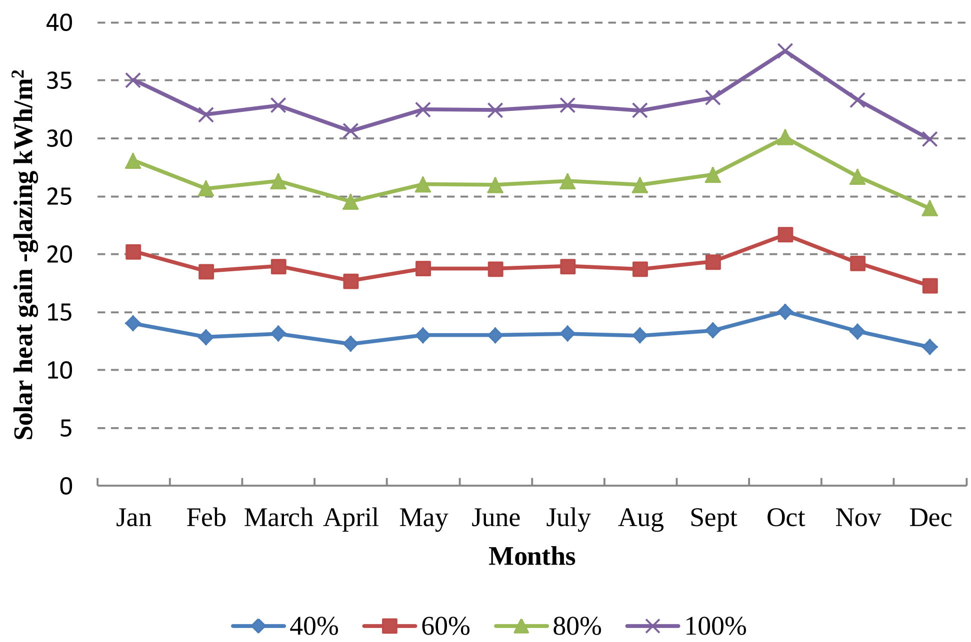
a)



b)

Figure 4.1 Monthly Energy breakdown (a) Lighting energy consumption (b) Cooling energy consumption

a)



b)

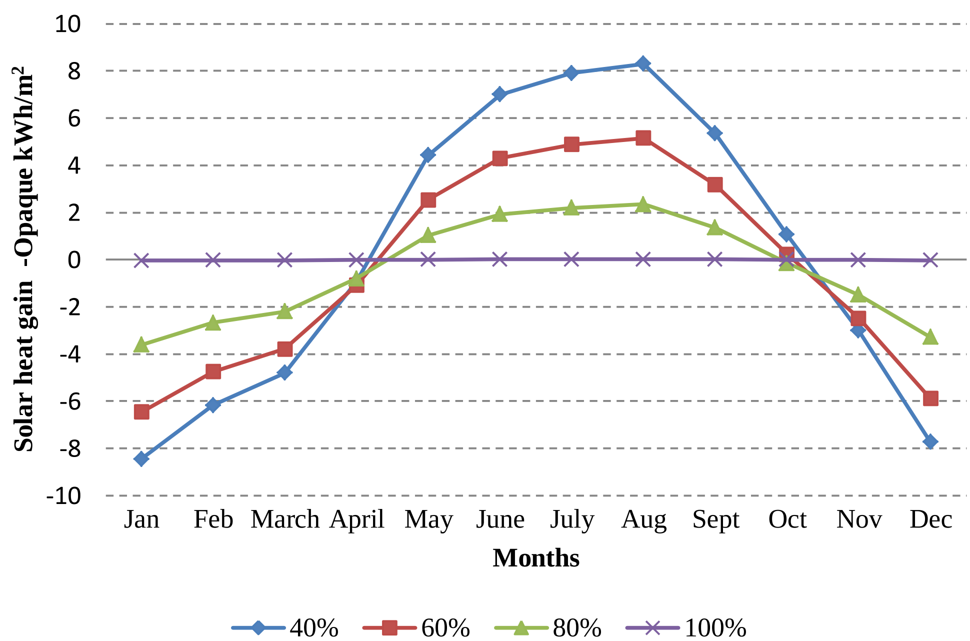


Figure 4.2 Monthly Solar heat gain – Envelope (a) Solar heat gain through glazing (b) Solar heat gain through opaque surfaces

4.1.2 Morphological actions

To analyze the impact of morphological actions on heat gain and energy consumption, **"simple generic"** forms, were modeled and analyzed. The base case with 100% WWR was utilized and morphed in levels to analyze the impact of form on heat gain and energy consumption.

The three levels of modeling are as follows:

Level 1 transformation

Morphing the base case using an independent action. These forms include-

Form "b": The form is developed by "**compacting**" the base case by reducing the exterior surface area by making the floor plans octagonal rather than square. The resultant form was an octagonal prism.

Form "c": The form is generated by "**skewing"** the base case at 90^{o}. The form is broader at the top and bottom in comparison to the apex.

Form "d": The form is generated by "**tapering**" the base case outwards by 7^{o}.

Level 2 transformation

Application of a second degree of morphological transformation. This involves morphing the form in two levels by using two actions at a time. These forms include-

Form "e": This form is a combination of **b** and **d.**

Form "f": This form is a combination of form **b** and **c.**

Form "g": This form is a combination of form **c** and **d.**

Level 3 transformation

The third degree of transformation involves application of all the studied morphological actions to the base case.

Form "h": This form is a combination of form **b, c** and **d.**

The resultant eight building forms and the levels of transformation are represented graphically in **Fig 4.3**.

These building forms were analyzed in Ecotect to obtain the values for PI-2. Form "b" was found to be the most compact form since it reduced its exposed surface area by 8.3% while form "g" was the most non-compact form which increased its exposed surface area by 12%.

Form "h" was the most prominent in reducing incident radiation (by 26.7%) by reducing both direct and diffused radiation by 27.3% and 25.3% respectively.

Summary of the PI's corresponding to building forms is specified in **Table 4-2**.

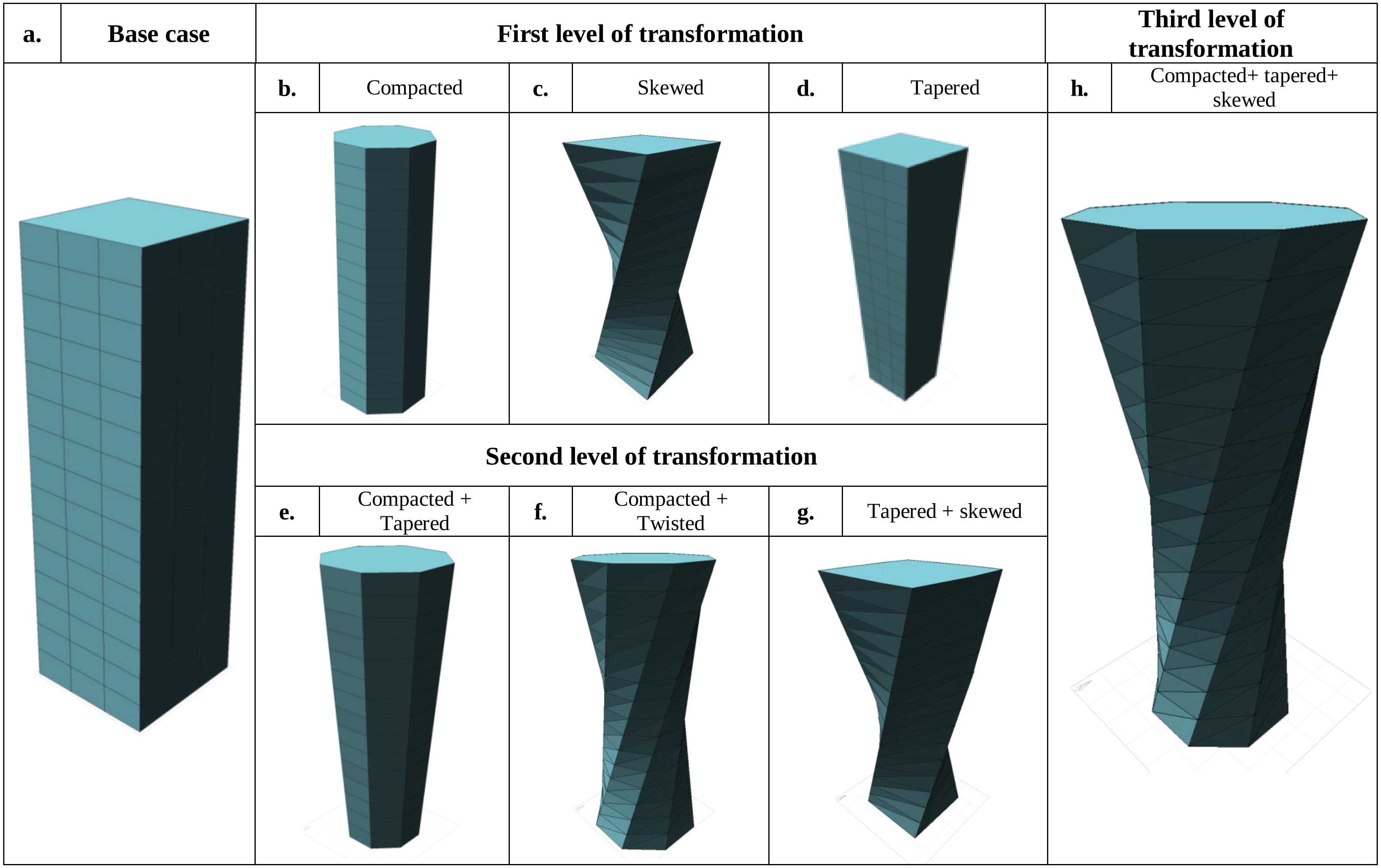
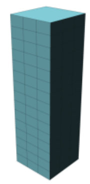
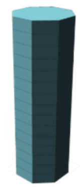
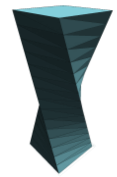
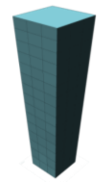
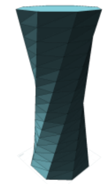
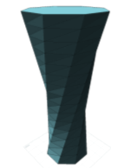


Figure 4.3 Levels of Form transformation

Table 4-2 Paramteric Evaluation of Simple generic forms

			Form a	Form b	Form c	Form d	Form e	Form f	Form g	Form h
										
PI-1	**Compactness**	Value (m^2/m^3)	0.215	0.197	0.236	0.218	0.20	0.209	0.238	0.213
		Variation from base		**-8.37%**	**10.01%**	**1.38%**	**-6.82%**	**-2.60%**	**10.7%**	**-0.99%**
i	**Exposed surface area**	Value (m^2)	5800	5315.18	6147.08	6066.45	5569.91	5559.81	6499.07	5907.39
		Variation from base		**-8.36%**	**5.98%**	**4.59%**	**-3.97%**	**-4.14%**	**12.05%**	**1.85%**
ii	**Inner Volume**	Value (m^3)	27000	27002.4	26011.84	27855.53	27826.16	26571.5	27330.76	27775.6
		Variation from base		**0.01%**	**-3.66%**	**3.17%**	**3.06%**	**-1.59%**	**1.23%**	**2.87%**
PI-2	**Incident radiation**	Value ($kWh/m^2/yr$)	740.1	626.71	747.2	670.64	567.41	630.2	653.3	542.5
		Variation from base		**-15.32%**	**0.96%**	**-9.39%**	**-23.33%**	**-14.85%**	**-11.73%**	**-26.70%**
i	**Average direct radiation**	Value ($kWh/m^2/yr$)	530.4	457.74	537.32	471.46	406.83	461.25	458.59	385.70
		Variation from base		**-13.70%**	**1.30%**	**-11.11%**	**-23.30%**	**-13.04%**	**-13.54%**	**-27.28%**
Ii	**Average diffuse radiation**	Value ($kWh/m^2/yr$)	209.70	168.97	209.88	199.18	160.58	168.95	194.71	156.8
		Variation from base		**-19.42%**	**0.09%**	**-5.02%**	**-23.42%**	**-19.43%**	**-7.15%**	**-25.22%**

4.1.3 Simulation Results

Energy simulation was carried out on these forms to analyze the impact on heat gain and energy consumption and results are summarized in **Table 4-3**.

Form “c” was able to reduce energy consumption marginally by 0.14%. It increased the incident radiation and compactness as a result of its form resulting in higher heat gain through glazing during the summer months. The heat gain during the period of October-March was lesser than the base case as seen from **Fig 4.4**.

Form “d” showed slightly higher levels of improvement by increasing energy savings by 1.6%. It was 1.3% lesser compact than the base case, and reduced incident radiation by 9.4%.

Form “g” conserved energy by 2.9%. Though it increased compactness to 0.23, it reduced incident radiation by 11.7% resulting in 8.1% reduction in cooling energy.

Form “f” lead to a saving of 3.0%.

Form “b” was the most compact form with compactness of 0.19 m^2/m^3 complimented by a prominent reduction in incident radiation. This led to significant savings of 3.2% in energy consumption.

Form “e” showed a leap in improvement by 4.9% as a result of the form being the second most compact form.

Form “h” was the highest energy efficient form amongst the studies, which has a resultant energy saving of 6% .This, can largely be attributed to the fact that this form had undergone all levels of transformation i.e. compacted, skewed and tapered. The accumulation of positive properties in a single form resulted in the form having the least amount of incident radiation resulting in reduction of heat gain by 15.5% from the base case. Thereby the cooling loads reduced by 8.4%. **Fig 4.4** illustrates the “heat gap” between the base case and form “h”.

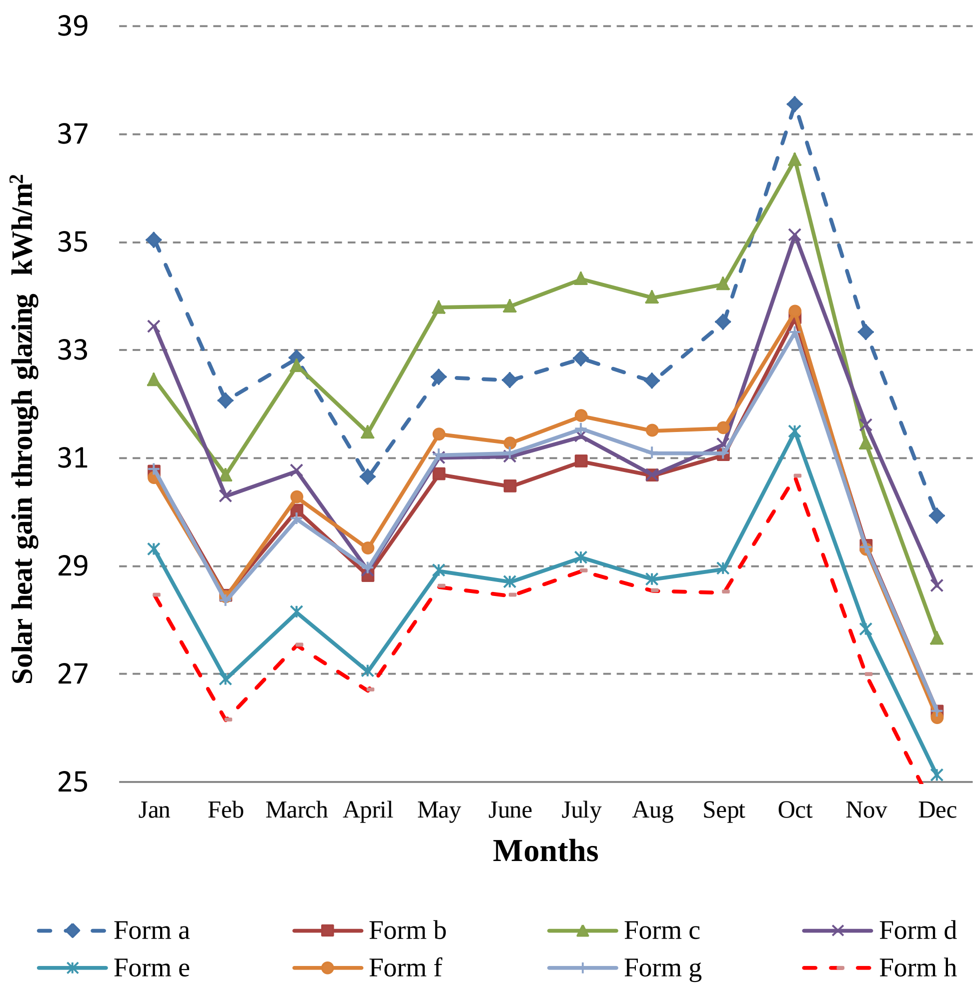
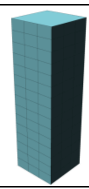
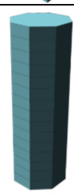
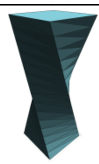
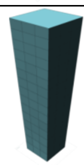
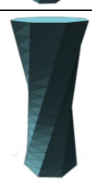
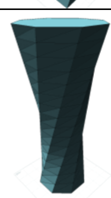


Figure 4.4 Annual solar heat gain through glazing

Table 4-3 Simulation results of Simple generic forms

Parametric Form		Annual solar heat gain-Glazing kWh/m^2		Annual Cooling Energy Consumption kWh/m^2		Total Annual Energy Consumption kWh/m^2	
a		**395.07**		**137.88**		**190.92**	
		Total	Variation	Total	Variation	Total	Variation
b		361.17	**-8.58%**	131.67	**-4.50%**	184.72	**-3.25%**
c		394.88	**-0.05%**	137.6	**-0.2%**	190.65	**-0.14%**
d		374.12	**-5.30%**	134.6	**-2.38%**	187.70	**-1.69%**
e		340.27	**-13.87%**	128.30	**-6.95%**	181.38	**-5.00%**
f		365.41	**-7.50%**	132.08	**-4.21%**	185.14	**-3.03%**
g		362.80	**-8.17%**	132.11	**-4.18%**	185.24	**-2.98%**
h		333.84	**-15.50%**	126.27	**-8.42%**	179.41	**-6.02%**

Note : (-) indicates a reduction (improvement from base case)

4.1.4 Correlation Analysis

In order to obtain the relation between the parameters and the magnitude of their influence, a correlation analysis was carried out between the relative parameter of forms to the relative cooling energy consumption. PI-1 had a correlation coefficient of 0.54 and hence it can be concluded that in case of contemporary forms, compactness has minimal impact on energy consumption.

Similarly a correlation was conducted on PI-2 and the results indicate a very strong positive correlation between relative incident radiation and relative cooling energy consumption (**Fig 4.5**). This indicates that as incident radiation increases, cooling energy consumption increases.

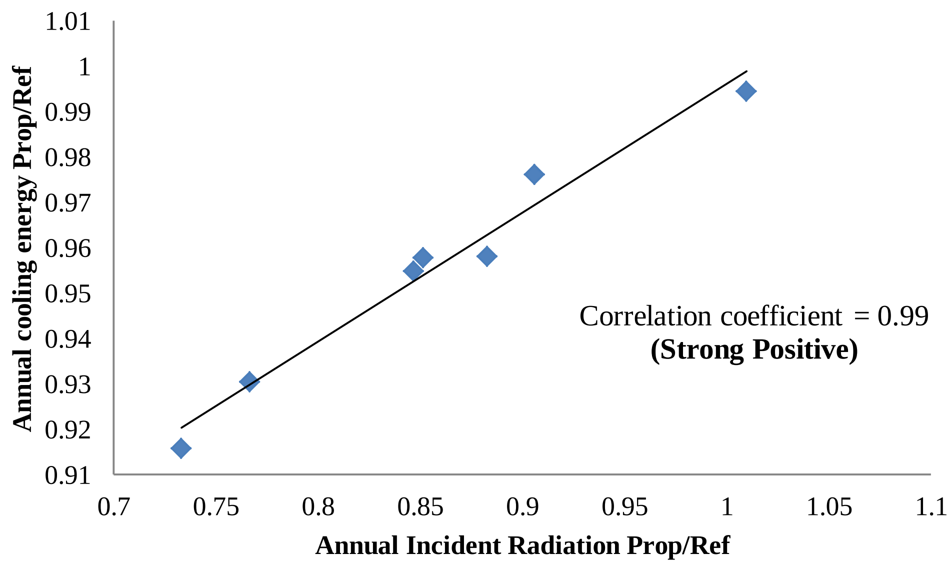


Figure 4.5 Correlation analysis: PI-2

4.2 Case study forms- PI evaluation

After conducting the Preliminary investigation, the case study forms were simulated and analyzed for their energy performance.

Similar to the preliminary simulation, The PI's were gathered using design builder and Ecotect. Solar access analysis was conducted from 6am to 6pm to acquire PI-2. **Table 4-4** compares all the PI's and the percentage of deviation from the base case. As seen from the table, Form **E** was the most compact form i.e. 18% more compact than the base case, as a result of its reduced exposed area i.e. 20.2% lesser than the base case, and at the same time, the lowest incident radiation (18.3% lower than base case). This low incident radiation can also be attributed to reduced angle of incidence at the lower levels of the form due to outward surface tilts (ranging from -1.62^o to -6.65^{o}from vertical). Similarly no surface was found to be at 90^o from vertical i.e. a perfectly horizontal surface that would receive the maximum radiation. The highest surface tilt was found to be 80^o.

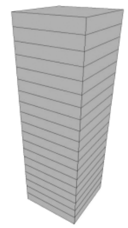
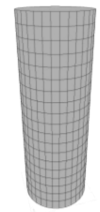
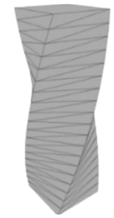
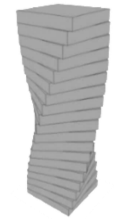
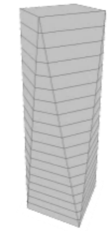
Form **B**, **E** and **F** had shown improvement in both PI's; with form **B** showing higher levels of improvement.

Form **C** showed lower compactness (+5.64%) as a result of its higher exposed area of 2.6% than Form **A**. The higher exposed area is a result of the glazing "bulges" created due to the twisted profile of the form. These bulges created triangular tilting of the glazing in angles of +13.5^o and -13.5^o. Collectively this resulted in an increase in direct radiation by 2.8% further resulting in an increase in total incident radiation by 2.3%.

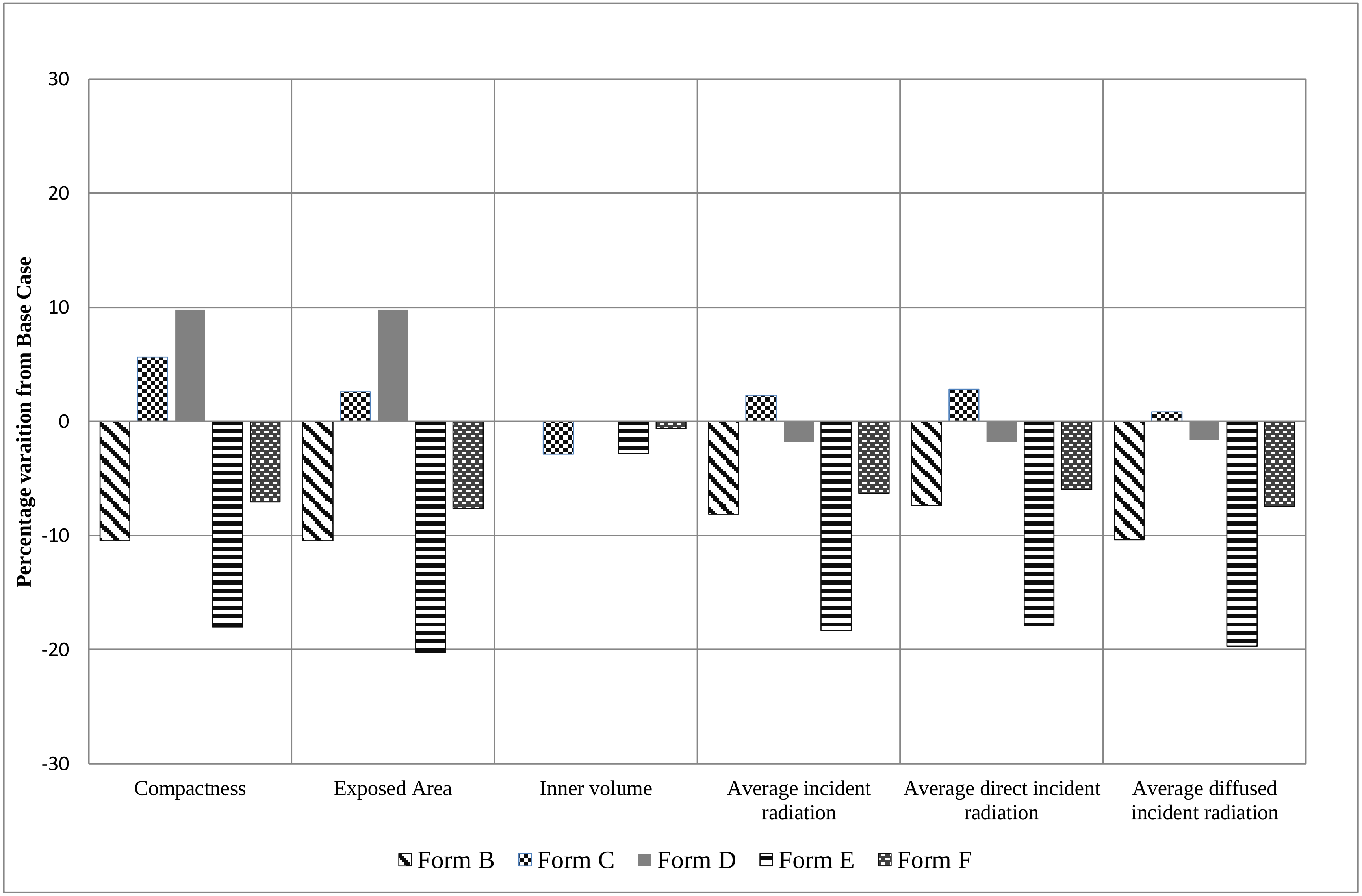
Form **D** had two unique entities emerging from each floor i.e. exposed roof areas and exposed external floors. Though this form had the same twist as Form **C**, the extra exposed surfaces (9.8% higher than Form A) affected the incident radiation. The external “roofs” receive direct and diffused radiation while the external “floors” receive diffused radiation and contribute to the total. However the external floors cast shadows on portions of the vertical glazing below thereby blocking some of the direct radiation. Moreover the twisted profile creates different orientations in for each floor thereby creating a distribution of radiation. The results indicate that the form reduced incident radiation by 1.76%.

The graphical summarization of the PI evaluation is depicted in **Fig 4.6**.

Table 4-4 Parametric Evaluation of case study forms

			Form A	Form B	Form C	Form D	Form E	Form F
								
PI-1	**Compactness**	Value (m^2/m^3)	0.171	0.153	0.181	0.188	0.14	0.159
		Variation from base case	**0%**	**-10.47%**	**5.64%**	**9.81%**	**-18.0%**	**-7.09%**
i	**Exposed surface area**	Value(m^2)	9175	8214	9415	10075.18	7315.36	8471.84
		Variation from base case	**0%**	**-10.47%**	**2.62%**	**9.81%**	**-20.27%**	**-7.66%**
ii	**Inner Volume**	Value(m^3)	53437.5	53436.09	51905.72	53437.5	51956.48	53109.6
		Variation from base case	**0%**	**0%**	**-2.87%**	**0%**	**-2.77%**	**-0.61%**
PI-2	**Incident radiation**	Value($kWh/m^2/yr$)	665.42	611.18	680.79	653.68	543.26	623.17
		Variation from base case	**0%**	**-8.15%**	**2.3%**	**-1.76%**	**-18.35%**	**-6.34%**
i	**Average direct radiation**	Value($kWh/m^2/yr$)	495.01	458.48	508.96	485.98	406.47	465.46
		Variation from base case	**0%**	**-7.37%**	**2.81%**	**-1.82%**	**-17.88%**	**-5.96%**
ii	**Average diffuse radiation**	Value($kWh/m^2/yr$)	170.41	152.7	171.83	167.69	136.79	157.71
		Variation from base case	**0%**	**-10.39%**	**0.83%**	**-1.59%**	**-19.72%**	**-7.45%**

Note: (-) indicates a reduction (improvement from base case)



Note : (-) indicates a reduction (improvement from base case)

Figure 4.6 Summary of PI evaluation

4.3 Case study forms- Energy Simulation

After gathering and evaluating the parametric inputs, the base case was simulated using design builder and energy plus, with the inputs specified in section 3.1. The case study forms will then be simulated using the same inputs to obtain and compare the Annual energy consumption (AEC).

The simulation will also be conducted to assess heat gain and its impact on cooling load, variation in thermal comfort and emission of carbon dioxide for the forms respectively.

4.3.1 Annual energy consumption

The results of the simulation reveal that the total AEC of the base case (Form A) was **184.3 kWh/m^2**. 71.3% of this electricity was dedicated towards cooling, 20.1% towards general room electricity, 8.4% towards lighting and a very insignificant 0.03% for heating. This low heating energy consumption also implies that it is not a major determinant while calculating AEC.

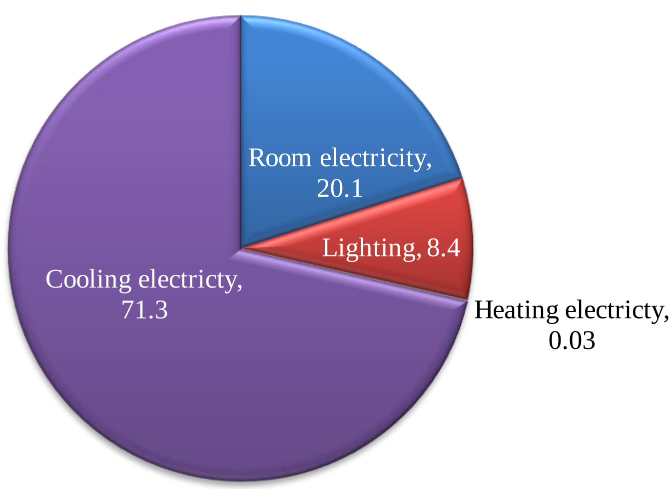


Figure 4.7 Energy end use -Base case

Using the same inputs as the base case, all the case study form were simulated.

It was found out that most of the case study forms had energy efficiency higher than the base case with the Form **B** being the most efficient one, which reduced both AEC and carbon emission by **6.1%** each. The total AEC was found to be **173 kWh/m^2**, and the total carbon emission was 104839kg. The reduction in AEC can be attributed to the performance high performance in both the PI's.

The second highest energy efficient form was Form **E** which had an AEC of **178.45 kWh/m^2,** representing a **3.2 %** saving and the same **3.2%** reduction in carbon emission. The compactness of the form contributed significantly in reducing the external area by a significant 20.2% and at the same time reduced the inner volume by 2.7%. The impact of this reduction is further explored in section 4.3.3.

Form **F** form showed a **2.4%**reduction in AEC. **(179.7 kWh/m^2)**. and a 2.5% reduction in carbon emission.

Form **D** showed the least improvement in energy efficiency out of remaining case study forms. The AEC was found to be **181.9 kWh/m^2**, representing a 1.3% reduction in consumption and carbon emission as compared to the base case.

Form **C** however showed a negative impact on energy consumption. The AEC was found to be **186 kWh/m^2**. This represented an increase in energy consumption and carbon emission by 0.9%. The increase in consumption can be majorly attributed to increase in solar heat gain as a result of increase in incident radiation.

Fig4.8 indicates percentage improvement/downturn of energy consumption and carbon emission for all case study forms as compared to base case.

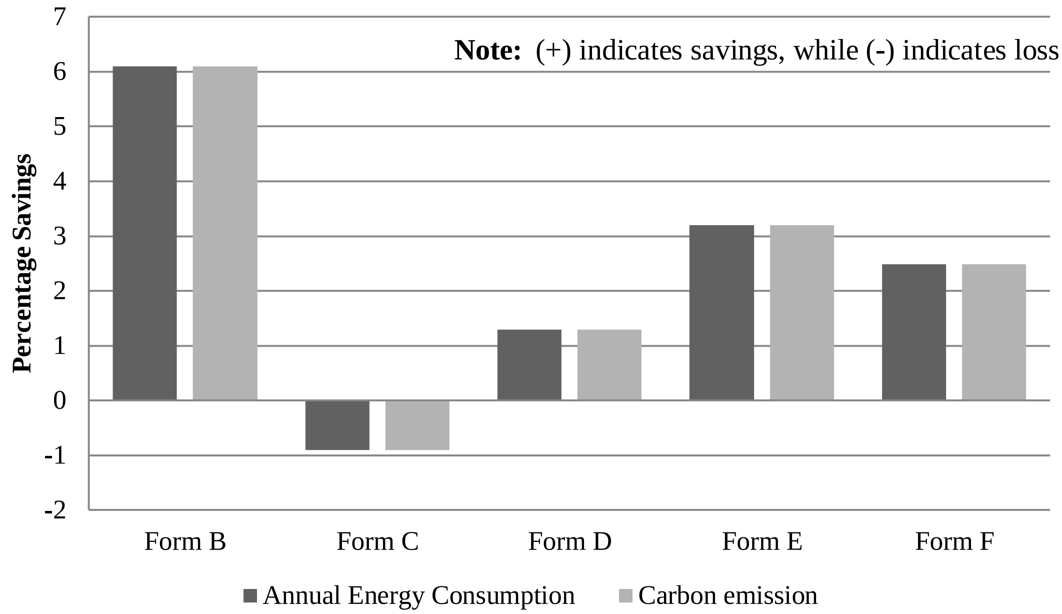


Figure 4.8 Percentage improvement compared to base case

There are two observations that can be made at this stage.

- The AEC and carbon emission and directly proportional to each other. i.e. a 1% saving in AEC will result in 1% reduction in carbon emission as well.
- Both forms which have a "curvilinear" profile were able to reduce energy consumption the most.

4.3.2 Solar heat gain and cooling energy

Cooling energy is the chief consumer of energy in all the studied forms, constituting 69-72% of the total energy for all the forms. And as a result, an increase or decrease in cooling energy will significantly impact the AEC.

The cooling energy was found to fluctuate significantly from form to form; with Form **B** being able to reduce the consumption by 8.6%.This was followed by Form E (4.5%), Form F (3.5%) and Form D being the least reducer (1.8%). However, Form C increased cooling energy consumption by 1.2%. This reduction /increase in cooling energy is in harmony with their resultant AEC's. **Fig 4.9** illustrates the cumulative annual cooling energy consumption of all the studied forms in kWh/m^2/yr.

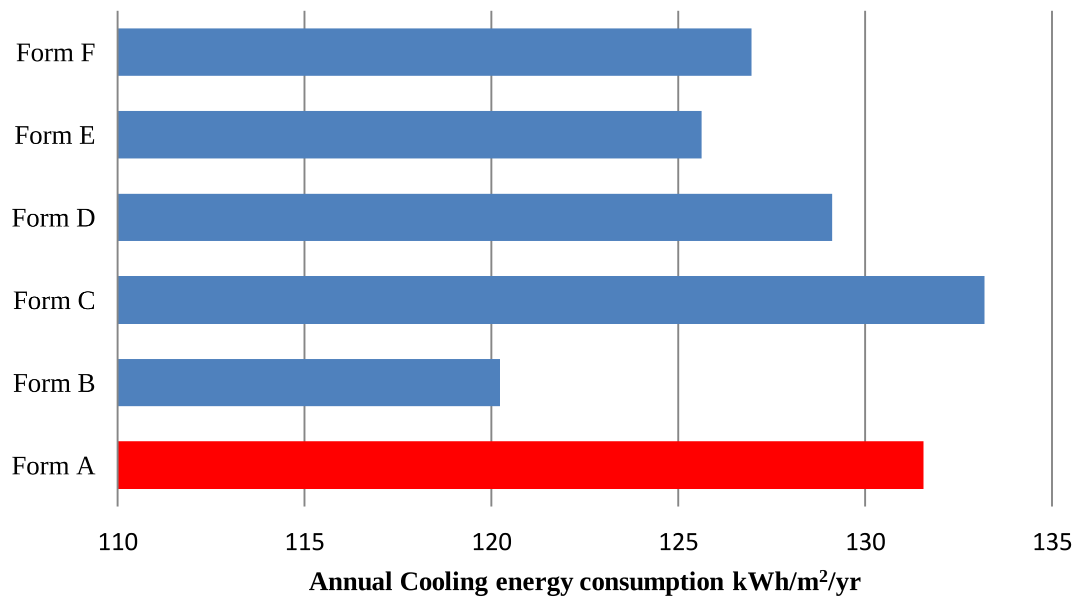


Figure 4.9 Gross annual cooling energy

The difference between the best performer (Form B) and worst performer (Form C) was about 13kWh/m^2/yr. The difference in consumption is prominent during the summer months as shown in **fig 4.10**, where the difference in cooling energy of 2kWh is constant from June – august.

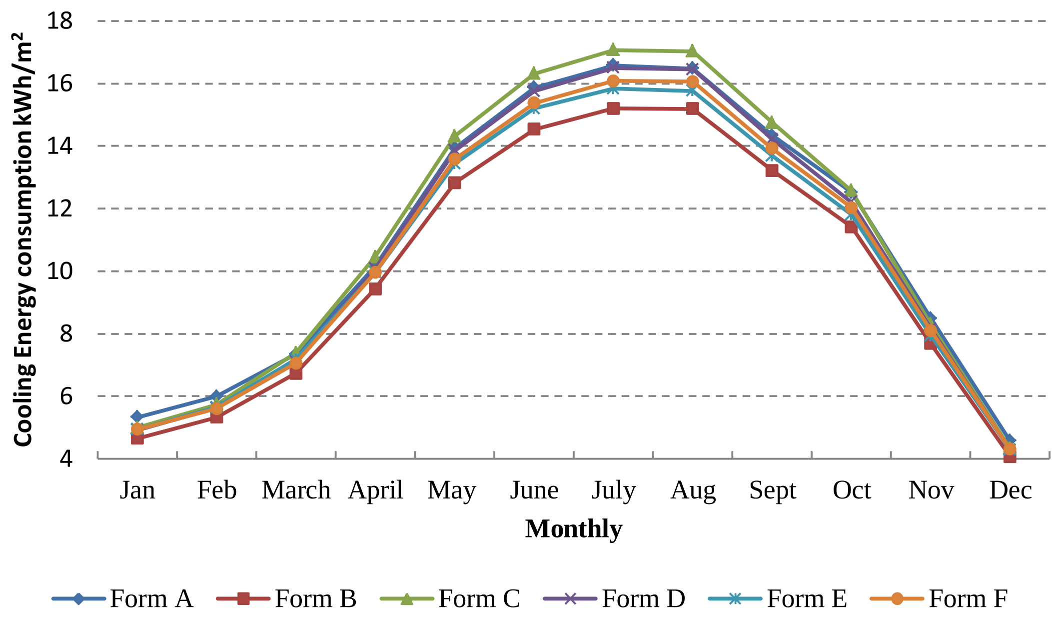


Figure 4.10 Cooling energy consumption - Monthly

The total load placed on the cooling system is as a result of:

- Internal gains such as heat from computers, heat generated from lighting, and occupants.
- External gains from building envelope and gains from infiltration.

Since Internal gains are determined directly by occupiable floor area, and the fact that all the forms have the same occupiable area, the cooling load placed by internal gains remains same for all the forms.

Heat gain from air infiltration was found to vary between 2.08 kWh/m^2/yr and 2.17 kWh/m^2/yr. This indicates that neither the values deviate significantly, nor is the heat gain prominent enough to influence energy savings.

The only source of heat gain that fluctuates from form to form remains the envelope.

a) Solar heat gain through fenestration:

As illustrated in **Fig 4.11**, Form **B** shows the least transmittance of solar gains through glazing as compared to other forms by reducing heat gain by 10.72% as compared to the base case. This is also a prime factor for its lower annual cooling energy, and as a resultant lower AEC.

Form **C** shows the highest heat gain through glazing; an increase by 2.8%, resulting in higher annual cooling energy which further leads to its high AEC. It also shows a decrease in solar heat gain during winters which goes in harmony with their higher heating energy consumption during winters.

Form **E** also shows higher heat gain during the summer periods, but it must be recalled that the form demands a “uni-form” design, which means that the vertical glazing continues to form the roof area. As a result the roof area is also glazed and the results in **Fig 4.12** are a combination of both vertical glazing and roof glazing. Form **D** and Form **F** show a reduction of 3.9% and 4.2% respectively.

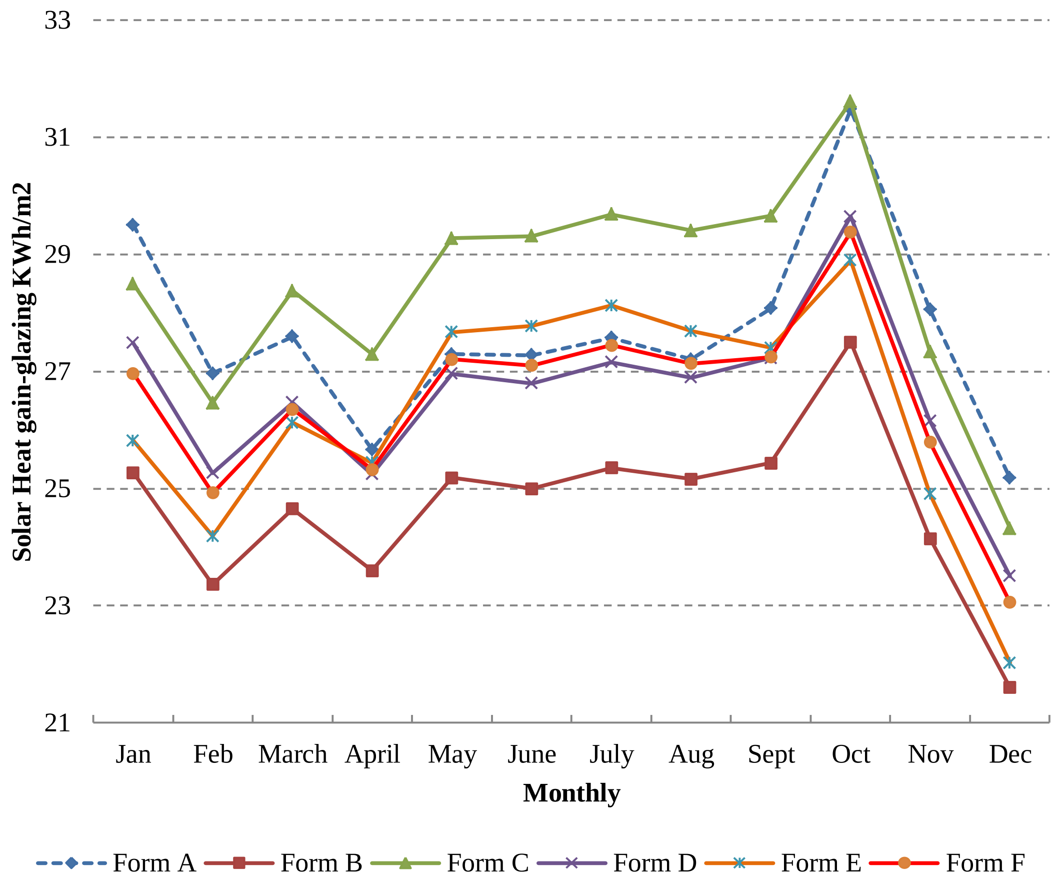


Figure 4.11 Comparison of monthly Solar heat gain – Glazing

b) Solar heat gain through opaque surfaces:

The opaque surfaces of the forms include the roofs and in case of Form **D**, the exposed external floors and exposed parts of roof projected from individual floors as well.

As seen from **Fig 4.12** the Form **E** shows zero heat gain through roofs. This is simply due to the design factor of the form that allowed no flat roof and had glazing instead.

Form **F** had the second least heat gain through roofs, as a result of its smaller roof area as compared to other forms.

Form **B** and Form **C** have a very similar heat gain response as the base case. This is as a result of same roof area.

Form **D** shows the highest heat gain through. This can be attributed to the design of the form itself which exposes small portions of roofs and external floors in every floor. As a result, the exposed opaque area increased, leading to higher heat gain. The form also creates excess heat loss during the winters which may increase heating energy.

Despite the higher heat gain through opaque surfaces, the total heat gain during the summer was calculated as 0.6kWh/m^2. This was insignificant in comparison to heat gain through glazing which was 164.7kWh/m^2.

Thus it can be safe to assume that in the current study, heat gain through opaque elements was not a major determining factor in determining energy consumption.

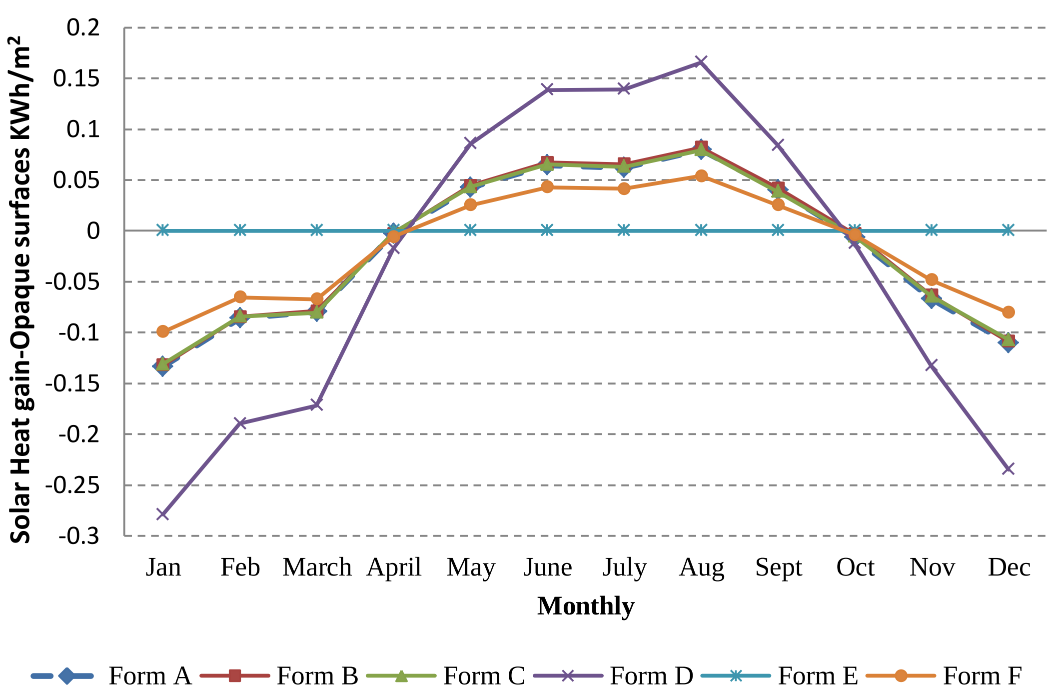


Figure 4.12 Comparison of monthly Solar heat gain/loss – Opaque surfaces

4.3.3 General consumption and lighting

Since the occupiable floor area is same in all buildings, the general room electricity i.e. plug and play load, remained constant for all buildings.

Apart from this, the lighting energy showed marginal fluctuation, with the base case being the most efficient one and the worst case was Form **E**, with just a 0.36% increase in consumption (**Fig4.13**). The marginal fluctuation in lighting energy can be attributed to:

- 1:1 Aspect ratio of the buildings
- Same WWR
- Same visual light transmittance of glazing
- Minor change in floor geometries
- Presence of light controlling sensors.

This Indicates that in the current study, lighting, heating and general electricity are not major influencing factors in determining energy savings when building form is to be examined.

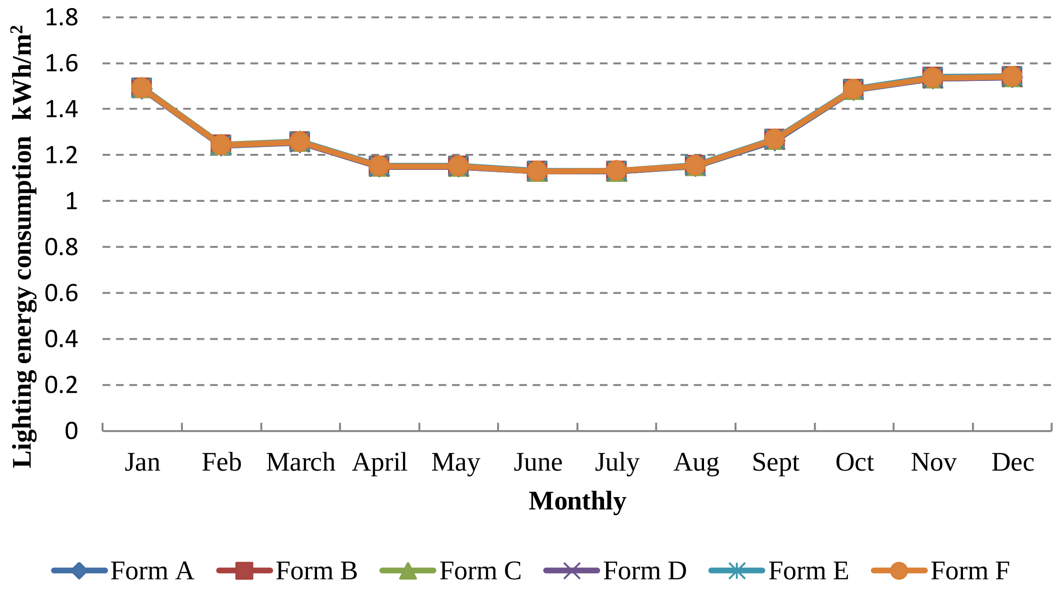


Figure 4.13 Lighting Energy Consumption

4.3.4 Comfort

Fanger developed a scale i.e. Predictive Mean Vote (PMV) to assess thermal comfort. The scale uses an index of thermal sensation of occupants to determine the comfort levels. The scale ranges from 3 to -3. Index 0 represents comfortable limit. +1 indicates slightly warm sensation, +2 indicates warm and + 3 indicates very hot sensation. Similarly the scale works inversely for cooling. -1 indicates slightly cool sensation, -2 indicates cool and -3 indicates very cold sensation. A building is said to be comfortable if its comfort sensation lies between +0.5 and -0.5.

All forms were found to lie within the band of +0.5 and -0.5 (**Fig 4.14 (a)**) and can be accepted as thermally comfortable.

However it is essential to calculate the discomfort hours during occupancy period with respect to clothing level.

Fig 4.14 (b) represents discomfort hours during the summer with clothing of clo 0.5. The base case has the highest discomfort hours (68hrs). Despite being the most energy efficient form, Form B did not possess the least discomfort hours. It had 53 hours as discomfortable which is 21hrs higher than the most thermally comfortable form i.e. Form **F** with only 31 hours as discomfortable. Also, Form **C** which was inefficient in saving energy was able to reduce 2.3hours of discomfort as compared to the base case.

Similarly the discomfort hours were calculated during the winter period with clothing level as 1.0 (**Fig 4.14(c)**).The base case again responded again as the worst case with 511 hours of discomfort. Similarly Form **F** performed the best with the value dropping to 448 hours, which was 63hrs lesser than the base case. Form **C** was the second most comfortable with a discomfort of 465hours, which is 46 hours lesser than the base case.

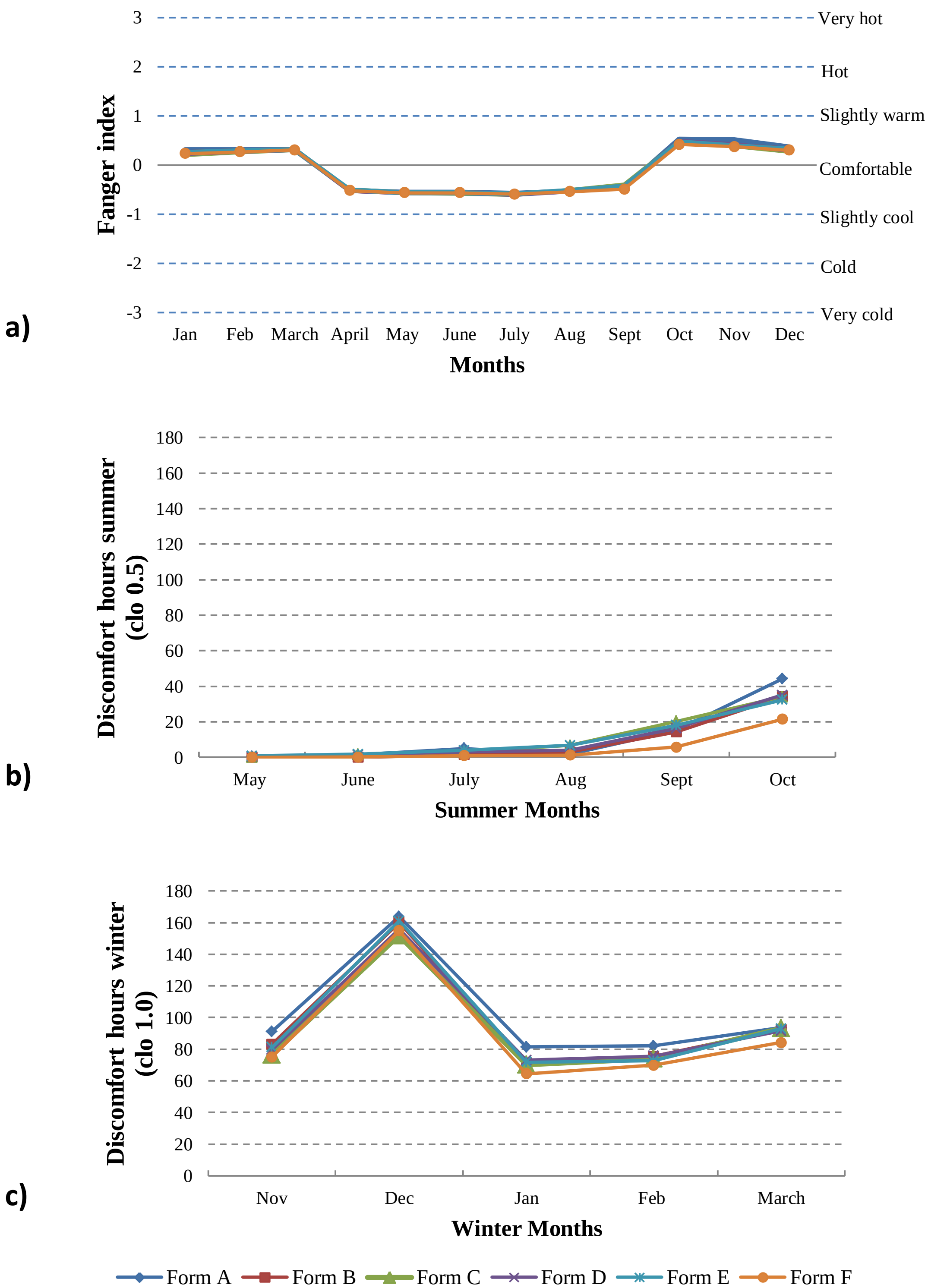


Figure 4.14 Thermal comfort analysis (a) Fanger PMV (b) Summer discomfort hours (c) Winter discomfort hours

4.4 Simulation Summary

The results of the simulation indicated that building form has a significant impact on AEC .This can be supported by the fact that all other energy influencing components such as occupiable area, Construction properties, and the office work schedule were kept constant while varying the building form alone.

General plug energy remained the same for all building forms, since its consumption was defined by usable area; which was same for all buildings.

Lighting energy fluctuated insignificantly indicating it as a non-major determinant of energy consumption variation.

Heating energy constituted a very non-significant 0.03% of total energy consumption and hence was excluded from detailed study.

Cooling energy remained the dominant determinant of AEC which ranged between 69 and 72% from form to form. Since cooling energy is dependent on heat gain, all the elements that contribute towards heat gain were analyzed. Since the number of occupants, their occupancy profile and lighting profile remained the same, heat gain from these two sources weren’t taken into account considering that they remain constant from form to form. Hence the envelope was defragmented into opaque and translucent areas and solar heat gain from these components was analyzed. Though the opaque components like roof did exhibit variation in heat gain, the gross heat gain through these opaque elements wasn't significant to influence energy consumption majorly. Similar was the response of heat gain due to air infiltration which found to be a non-major contributor.

Heat gain through glazing was found to significantly vary between forms and was found to majorly determine AEC of the forms. The simple cylindrical form (Form **B**) reduced heat gain through glazing by 10.7% and thereby able to reduce AEC by 6.1%

The twisted form (Form **C**) showed an increase in heat gain by 2.8% resulting in an increase in AEC by 0.9%. **Table 4-5** summarizes the simulation results.

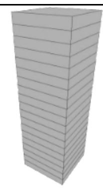
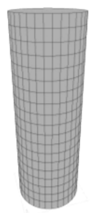
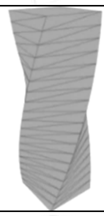
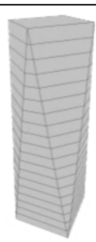
Thermal comfort analysis was also carried out which indicated that all the forms lie within fanger's thermally acceptable limit of +0.5 and -0.5. This was also a cross-check for cooling and heating setpoints.

It was also found that most energy efficient form wasn't the most thermally comfortable as well. The crystalline twisted form (Form **F**) showed the least discomfort hours in both summer (31hrs) and in winter (448hrs). While the base showed the highest discomfort hours (68hrs in summer and 511hrs in winter).

Table 4-6 Ranks the forms based on their performance where rank 1 indicates the best performer while rank 6 indicates the worst. Form C was the best performer in terms of Annual solar heat gain through glazing (least gain), Annual cooling energy (least consumer), Annual heating energy (least consumer) and the Total Annual energy consumption (least consumer). Form C was a mirror of the ranking of Form B where it performed the worst (highest consumer) in the above mentioned attributes. For solar heat gain through opaque surfaces, Form E performed the best while Form D was the worst.

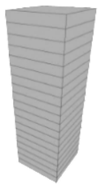
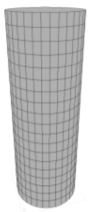
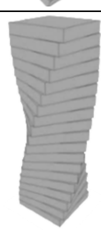
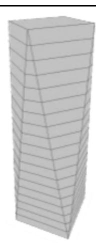
The base case performed the best in lighting energy consumption but had the worst summer discomfort hours. Form F performed the best in case of summer comfort.

Table 4-5 Simulation summary of case study forms

Parametric Form		Annual solar heat gain-glazing kWh/m^2		Annual Cooling Energy Consumption kWh/m^2		Total Annual Energy Consumption kWh/m^2	
A		**331.88**		**131.56**		**184.32**	
		Total	Variation	Total	Variation	Total	Variation
B		296.28	**-10.72%**	120.23	**-8.6%**	173.0	**-6.1%**
C		341.25	**2.8%**	133.20	**1.2%**	186.0	**0.9%**
D		318.82	**-3.93%**	129.11	**-1.86%**	181.19	**-1.3%**
E		316.07	**-4.76%**	125.63	**-4.5%**	178.45	**-3.2%**
F		317.96	**-4.2%**	126.95	**-3.5%**	179.74	**-2.5%**

Note : (-) indicates a reduction (improvement from base case)

Table 4-6 Annual Performance Ranking (Based on Annual Results)

Form designation	Form illustration	Solar Heat gain through glazing	Solar Heat gain through opaque surface	Cooling Energy	Lighting Energy	Heating Energy	Total Annual Energy	Summer Discomfort hours	Carbon Emission
A		5	3	5	**1**	4	5	**6**	5
B		**1**	3	**1**	3	**1**	**1**	4	**1**
C		6	3	**6**	5	**6**	**6**	2	**6**
D		4	**6**	4	2	5	4	5	4
E		2	**1**	2	**6**	3	2	3	2
F		3	2	3	4	2	3	**1**	3

4.5 Improvising inefficient forms

As per the results of the simulation, Form **C** was found to be an inefficient one, which increased energy consumption by 0.9%. However keeping in mind that the architectural ambition still has to be retained, and yet energy efficiency has to be achieved, the characteristics of the envelope have to be altered in order to achieve better thermal response and thereby reducing energy consumption.

From the results in section 4.3.2, it is evident that the glazing system of the studied forms shows substantial variation and as a result it can be concluded that it is the most impacted constituent of the envelope as a result of change in form. Thus the type of glazing can be modified in order to offset the negative impact on heat gain.

To achieve this, a variety of glazing systems were analyzed and compared. The main criteria in choosing the glazing systems were:

- Having the same VT as the baseline model so as to retain the same amount of lighting energy.
- Having lower U value in order to reduce conductive heat transfer.
- Having a better VT/SHGC. This ensures that the glazing system provides adequate lighting and as well as reduces heat gain through transmission.

As a result two glazing systems were chosen as represented in **Table 4-7**.

Case 1 glazing used the same type of glazing as the baseline except that the air space had been increased from 6mm to 13mm and air had been replaced by argon. This reduced the

U value from 3.23 W/m^2-k to 2.59 W/m^2-k. A slight improvement in VT/SHGC was noticed as it improvised from 1.19 to 1.21.

Table 4-7 Optimized glazing data

	Description	U- value (w/m^2-k)	VT	SHGC	VT/ SHGC
Baseline	Double green 3m/6mm Air	3.23	0.74	0.621	1.19
Case 1	Double green 3mm/13mm Arg	2.59	0.74	0.61	1.21
Case 2	Double Low E (e2=.1)Clr 6mm/13mm argon	1.49	0.74	0.56	1.32

The results of the simulation indicate that case 1 was able to reduce solar heat gains by a marginal 2.5% as a result of which the energy consumption dropped from 186.0 kWh/m^2/yr to 184.46 kWh/m^2/yr, indicating a 0.8% improvement. This however is still 0.07% higher than the base case.

Case 2 glazing was chosen as a low emissivity glazing with 6mm glass panes and 13mm air space with argon filling. The U value dropped significantly from 3.23 W/m^2-k to 1.49 W/m^2-k and the VT/SHGC ratio increased to 1.32.

As a result, the solar heat gain reduced by a substantial 10.9%. This led to reduction in energy consumption to 179.3 kWh/m^2 which is 3.73% better than the baseline and 2.72% better than the static base case.

Fig 4.15 Compares the Solar heat gain through glazing and cooling energy consumption for the baseline (Form **C**), Case 1, Case 2 all in contrast to the base case (Form **A**).

Similiarly, the glazing data provided in **table 4-7** was applied to the best case i.e. Form **B** to analyze how further the energy performance can be improved. The results are indicated in **Fig 4.16.**

a)

b)

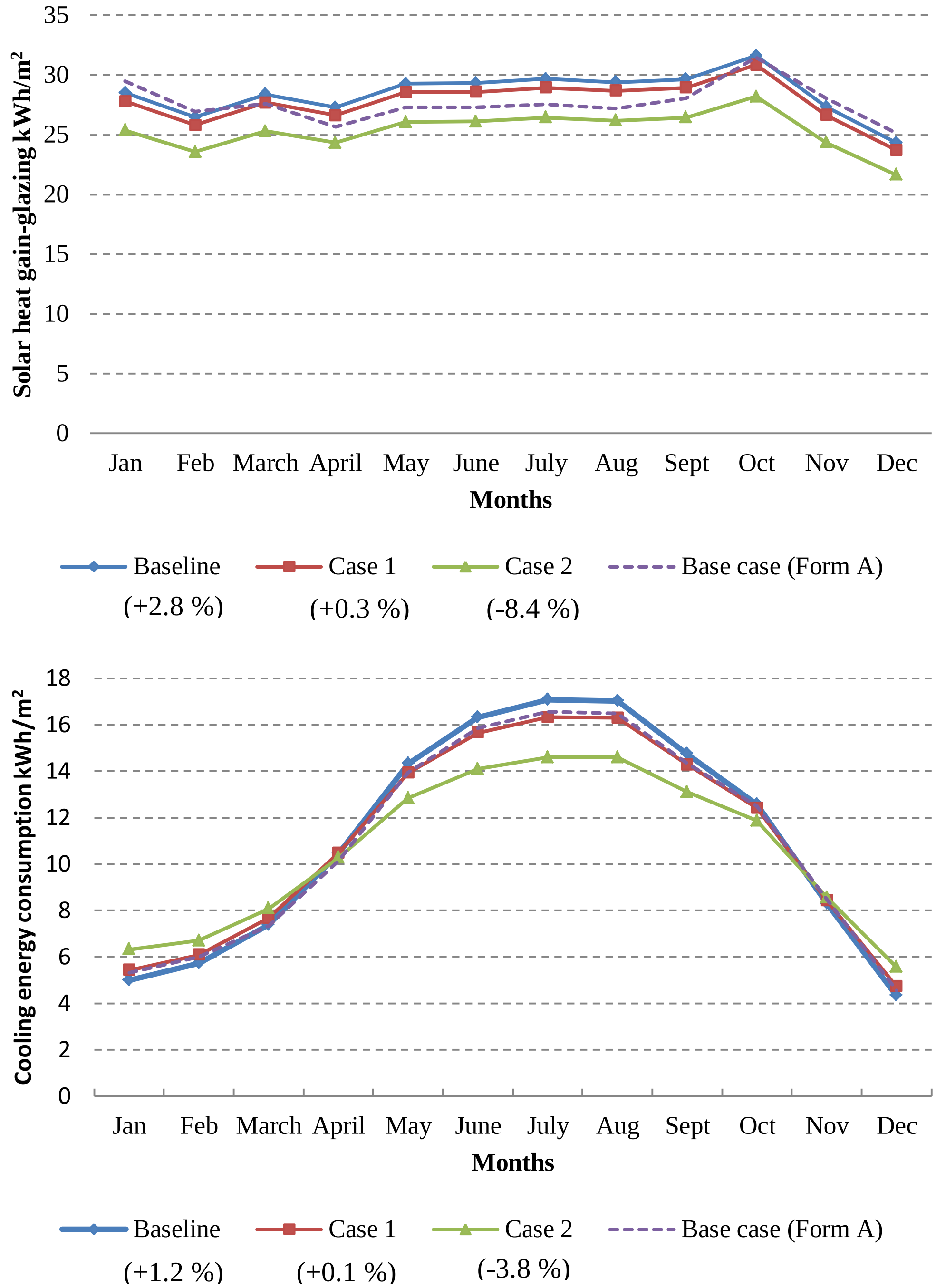
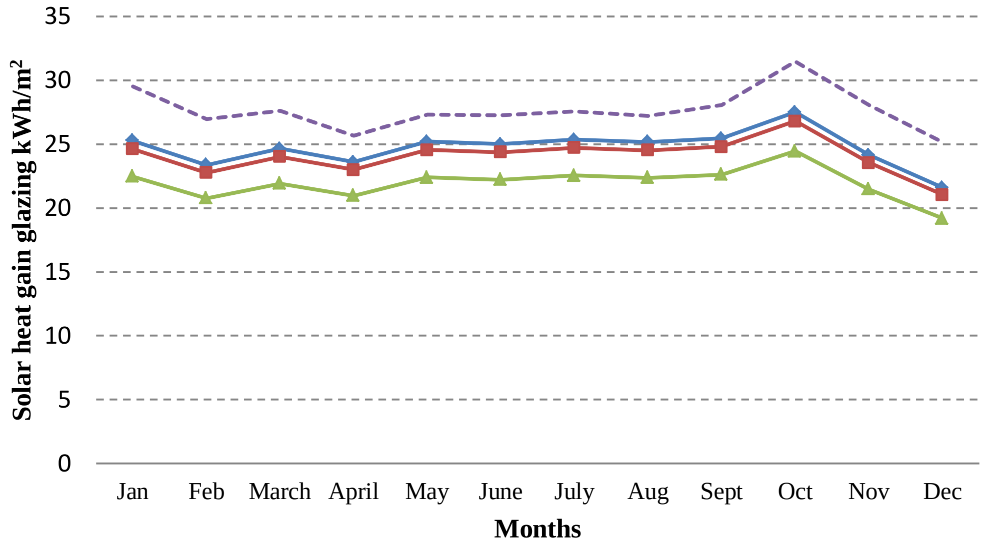
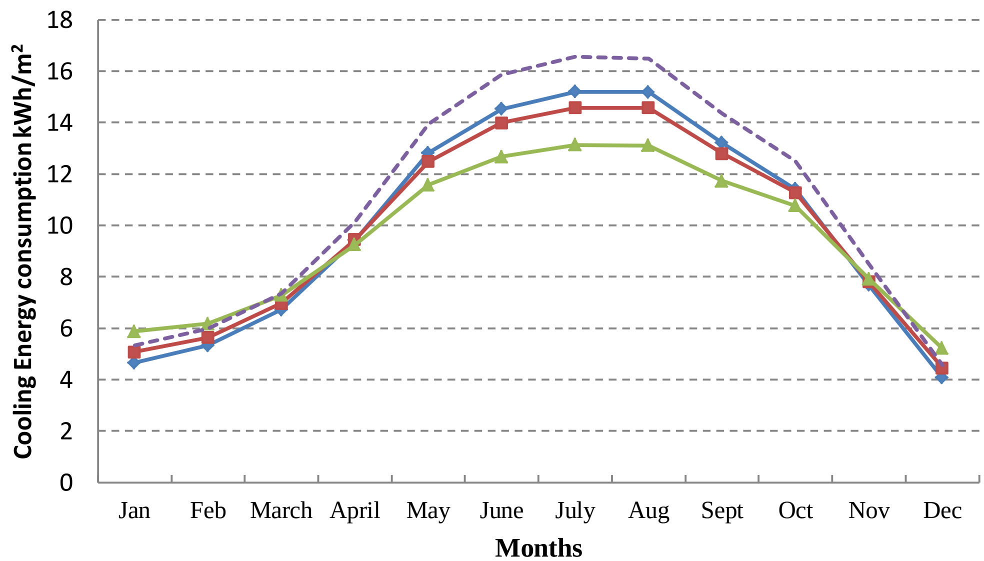


Figure 0.1 Monthly Comparison of (a) Solar heat gain-glazing and (b) Cooling energy consumption - Form C



a)



b)

Figure 4.26 Monthly Comparison of (a) Solar heat gain-glazing and (b) Cooling Energy Consumption – Form B

The energy consumption in case 1 dropped to a marginal 0.7% and in case 2 the energy consumption dropped to 3.23%.

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

In quest of assessing the impact of architectural design decisions on the sustainable environment, building form was identified as an element of study. A literature study was conducted on studies similar to building form and energy and essential parameters were gathered that influence heat exchange and energy savings the most. Thereby Compactness and incident radiation were found as significant contributors.

A preliminary study was conducted using simple generic models to analyze two key areas; firstly the impact of WWR on heat gain and energy consumption. This was done in order to analyze the energy performance when ASHRAE recommended 40% WWR is compared with current practices of utilizing a full glazed system. For this four different WWR namely 40%, 60%, 80% and 100% were selected. An increase in energy consumption by 19.1% was observed.

The second step of the preliminary study was to observe the impact of morphological actions on heat gain and energy consumption and weather it can offset the increase in solar heat gain as a result of using fully glazed system.

Hence the base case was morphed in levels namely first degree second degree and third degree .It was found that the third degree of transformation .i.e. application of all observed morphological actions resulted in the least solar heat gain, resulting in significant energy savings of 6%. The resultant energy consumption (179.4 kWh/m^2/yr) was close to the static base case with 80% WWR (178.4kWh/m2/yr).

A correlation analysis was carried out between the relative parameters and relative cooling energy. It was found out that incident radiation has the strongest correlation in contrast with other parameters.

The third part of the study involved modeling and simulation of existing building forms that have been altered to establish the same properties (such as the gross occupiable area, construction materials, occupancy and lighting profiles,etc) as a static cuboidal base case. In total five buildings were chosen as case studies and simulated.

It was found that both forms with curvilinear morphology showed the highest energy savings. The simple curvilinear form showed an energy saving of 6.1%. It was also found that the building form with a twisted profile showed a 0.9% increase in energy consumption. This can largely be attributed to its increase of external surface area, thereby resulting in lower compactness, and its higher incident radiation as a result of glazing inclination

The fourth part of the study proposes measures to improvise the energy efficiency of the worst case by proposing suitable glazing that has similar light transmission but lower solar heat gain coefficient and lower U value. As a result of modifying the glazing with the above mentioned criteria, a reduction of 3.73% in energy consumption was achieved. The same change in glazing was applied to the best case to analyze the range of further improvement. The energy consumption was improvised to a further 3.2%.

The study concludes that building form in sensitive to heat gain which thereby impacts the cooling energy consumption which further impacts the total energy consumption.

It can also be concluded that the correlation between energy parameters and energy consumption is different for static buildings and contemporary buildings. The literature study stated that compactness correlated strongly with energy consumption for static forms, but the current study reveals the results aren’t the same when contemporary forms are being examined.

5.2 Guidelines for Architects and designers

- Using the strategy of “form follows energy-efficiency” can help reduce energy consumption while creating aesthetically innovative form.
- Increasing WWR decreases Lighting energy consumption but not significant enough to offset increased cooling energy consumption, Hence the ratio has to be careful chosen to balance between aesthetics and energy efficiency.
- Controlling transparency and opacity in different orientation can help reduce heat gain while creating an asymmetrical architectural design.. Ex- the North façade is comparatively less affected by change in WWR and hence higher glazing ratio can be used in North while limiting it in the remaining facades.
- Inclining a building façade outwards from the vertical will reduce the angle of incidence and thereby reduce solar heat gain. Higher the angle-Higher will be the reduction. This will result in reduced Annual energy consumption. For practicality, the inclination shall be limited between -5^o and -40^o. The inclination can be avoided in the North direction since its impact on heat gain is minimal.
- Even if the form is kept static, the glazing (or) outer vertical façade can be morphed in a way to reduce incident radiation by giving suitable tilts and turns (surface morphology).
- Using a “twisted” building form in hot climates is not favorable as it increases incident radiation. It also poses comparatively lesser scope of improvement if thermal properties of the envelope are altered.

- Increasing the number of sides in a polygonal floor plan and keeping the floor area constant can comparatively reduce heat gain by reducing exposed surface area.
- Curvilinear forms perform better in hot climates in comparison to polygonal forms as a result of higher compactness.
- Using a combination of compactness and reducing incident radiation can result in more energy savings. Though in the current study, the results of the correlation indicate a moderate relation between compactness and energy consumption, it was found to impact significantly when used in combinations.
- Assigning a type of glazing that has higher VT/SHGC ratio will ensure better utilization of daylight transmission while reducing solar heat gain. This can be used to offset negative impacts of morphed building forms.

5.3 Recommendations

It is recommended that design builder gives more flexibility to model building forms so that the reliance on other modeling software to model geometries and then export it to design builder can be eliminated and reduce the amount of time and efforts.

Secondly when geometry is imported in design builder that is not at right angles to the horizontal, the software must allow the liberty to choose the window to wall ratio for the model directly, thereby reducing the efforts in drawing windows manually. The same scenario implies for Gmodeller where it should allow users to apply “window” material to non-vertical surfaces.

Thirdly the results of energy plus must also indicate cumulative results of incident radiation rather than displaying it for individual surfaces.

Fourthly a software can be designed that allows us to numerically enter parametric value and the software generates the form accordingly. This can help in analyzing the relation of contemporary forms and heat gain in much detail.

5.4 Future work

- This study had certain boundaries such as symmetry of facades in all orientations, usage of the aspect ratio 1:1 etc. These boundaries can be released so that the study can be extended further to examine the impact of morphological transformation if the facades are asymmetric, i.e. different configuration in different orientations .

- The study also revolved majorly around **two** identified parameters. The study can be extended by identifying and analyzing more parameters.
- The study was conducted in hot climatic conditions. It can be assessed in Moderate and Cold climates.
- All the contemporary forms examined in the study were fully glazed. The study can be extended to examining the impact with varying Window to Wall ratio.
- Furthermore the study can be extended with regards to life cycle costing.

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Vitae

Name	:**Ejaaz Ahmed**
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Academic Background	:Architecture
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Education:

- **2017:** Msc in Architectural Engineering (Environmental control systems) from King Fahd University of Petroleum and Minerals (KFUPM) with a CGPA of 3.65.

- **2014**: Bachelors in Architecture (Specialization in Interior design) from Jawaharlal Architecture and Fine Arts University (JNAFAU).Completed the course with distinction.

- **2009**: Intermediate (11th and 12th) from Sri Chaitanya Junior kalasala,, Hyderabad.

- **2007**: Schooling from St. Andrews High school, Hyderabad.

Academic Experience:

2015-2017, KFUPM:

- 2015-2017, Member of the “ARE promotion Committee” and head of the “Media Team”.
- 2017, Assistant Course instructor in ARE department, for “Architectural Design I” (ARE 202) course.
- 2017, Assistant Course instructor in ARE department for “Computer Applications in Building Design” (ARE 222) course.
- 2017,Jury member for the Course ARE 301 (Architectural Design II)
- 2016, Speaker for two seminars on 3d modeling (SketchUp) organized by the ARE club.
- 2016, Course instructor in ARE department for “Architectural Graphics” (ARE 101) course.
- 2016, Assistant Course instructor in ARE department for “Computer Applications in Building Design” (ARE 222) course.
- 2016, Assistant Course instructor in ARE department for “Architectural Design I” (ARE 202) course.
- 2016, Jury member for the Course ARE 301 (Architectural Design II).
- 2015, Course instructor in ARE department for “Architectural Graphics” (ARE 101) course.
- 2015, Assistant Course instructor in ARE department for “Architectural Design I” (ARE 202) course.

Architecture and Field Experience:

2014-Current: Ejaaz Viqar Architects (Principal Architect)

- Free lancing and taking up projects of all scales; In India and Gulf Region.
- Completing the undertaken project in terms of Conceptual development, space planning, Form development, interior designing, interior working drawings, exterior designing, material selection, finishing's, landscaping.
- Self-dealing with clients and site visits.

December 2013 - April 2014: Slicktech Architects (Internship)

- Planning and designing spaces of both commercial and residential types in 2d, and producing 3d views with material specifications and theme collaboration.
- Discussion and meetings with the clients, understanding their requirement and point of perspective.
- Site visits to ensure if design is being executed properly, and any additions or alterations if required.

June 2011- October 2013: MAS construction (Part time designer)

- Planning and designing spaces of both commercial and residential types in 2d, and producing 3d views with material specifications.

Certificates and Awards:

- **2017:** Award of Achievement for finishing Second place in Sustainable Building Competition, KFUPM
- **2017:** Certificate of Appreciation for playing an important role in the ARE club, KFUPM/
- **2014 :** Certificate of Excellence for Highest thesis score in the state, CSIIT, Hyderabad.

- **2013:** Certificate of Participation in Conceptual development of Memorial house of ex-chief minister of Andhra Pradesh, Samar Ram Chander Associates, Hyderabad.
- **2012:** Participated in Annual Architectural competition (NASA) and short listed amongst top 20 in India.

Software:

- Autodesk Autocad
- Autodesk Revit
- Autodesk Ecotect
- Adobe Photoshop
- Adobe illustrator
- Design Builder
- Trimble SketchUp
- Lumion
- Microsoft office